



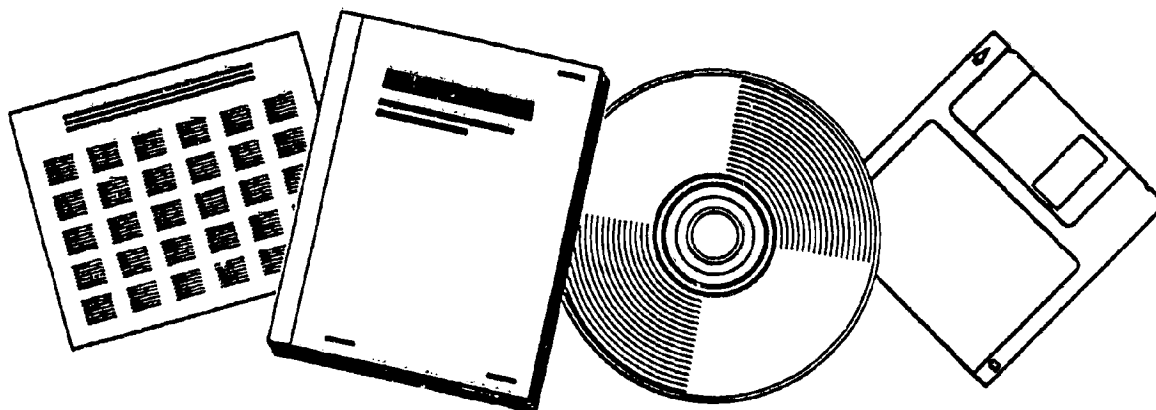
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ASSESSMENT OF REQUIRED ACCURACY OF DIGITAL ELEVATION DATA FOR HYDROLOGIC MODELING

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ASSESSMENT OF REQUIRED ACCURACY OF DIGITAL ELEVATION
DATA FOR HYDROLOGIC MODELING

by

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ABSTRACT

The effect of vertical accuracy of Digital Elevation Models (DEMs) on hydrologic models is evaluated by comparing three DEMs and resulting hydrologic model predictions applied to a 7.2 km² USDA - ARS watershed at Mahantango Creek, PA. The highest resolution (considered to be most accurate) of the three DEMs is a 5 m product derived by automated stereocorellation from low altitude aerial photography. The other two DEMs were the standard 30 m USGS 7.5' DEM, and a 30 m DEM produced by NASA's Jet Propulsion Laboratory using interferometric processing of Spaceborne Imaging Radar-C (SIR-C) imagery. The high resolution (5 m) DEM was resampled to a 30 m resolution using a method that constrained the spatial structure of the elevations to be comparable with the USGS and SIR-C DEMs. This resulting 30 m DEM was used as the reference product for subsequent comparisons. Spatial fields of directly derived quantities, such as elevation differences, slope, and contributing area, were compared to the reference product, as were hydrologic model output fields derived using each of the three DEMs at the common 30 m spatial resolution.

A statistical analysis of the difference between the USGS and reference DEMs found that the USGS DEM had a systematic error created during the DEM production process, as well as vertical error structure related to the topographic attributes of the watersheds. The SIR-C DEM was initially 50.5 meters lower than the reference product at the basin outlet, and was therefore uniformly elevated to match the USGS basin outlet elevation. The adjusted SIR-C DEM differed from the reference DEM by -34.3 to +48.1 m over the watershed, while the range of the USGS DEM differences from the reference was -22.1 to +27.0 m. ARC/INFO algorithms were used to delineate the watershed boundaries and to determine topographic parameters from each DEM. The watershed area of the USGS DEM was within 0.04 percent of the reference product's area, while the SIR-C DEM was 3.6 percent larger. The inaccuracies in the USGS and SIR-C DEMs were apparent in the drainage network which was visible in spatial images of elevation, slope and contributing area. The valley network was poorly defined and there were more meandering drainage channels in the USGS and SIR-C DEMs as compared to the reference product.

A spatially distributed, physically based hydrologic model was used to simulate runoff production in the Mahantango Basin for the four year period beginning October 1, 1983, using each of the DEMs. Mean annual runoff volumes for simulations that used the USGS and SIR-C DEMs were 0.3 and 7.0 percent larger, respectively, than simulations produced using the reference DEM. Differences observed in direct comparisons of topographic parameters were reflected in simulated spatial distributions of depth to saturation and runoff production; specifically, these properties were much less spatially coherent in simulations that used the USGS and SIR-C DEMs as compared to the reference. These differences were in turn reflected in the shape and timing of simulated runoff hydrographs; the USGS and SIR-C DEMs produced lower peak flows and higher base flows than the reference, with the differences most pronounced for the SIR-C product.

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1. Introduction

Developments in the acquisition, processing and storage of digital data have greatly increased the availability and reliability of digital elevation models (DEMs). The emergence of Geographical Information Systems (GISs) has provided a tool to analyze and manipulate spatial information such as DEMs, land use, soil and vegetation data. This capability has led hydrologic computer models to evolve towards spatially distributed simulations of watershed conditions based on physical processes.

Digital elevation data are widely available in the United States in different formats, resolution and accuracy. The primary source of these data is the U.S. Geological Survey's (USGS) series of one, three and 30 arc-second DEMs which are derived from digitization of contour maps and aerial photography. DEMs are also being derived by other agencies for specialized purposes from low altitude aerial photography, radar imagery, interferometry and altimetry. These new data sources combined with improved DEM production processes provides high resolution data over small areas (from low altitude aerial photography and laser altimetry) or greater spatial coverage at a lower resolution (from radar and interferometry onboard spaceborne platforms). The greater coverage of remotely sensed products is particularly advantageous for global and large-scale studies.

Distributed hydrologic models require elevation data to model topographic controls on incoming short-wave radiation, precipitation, air temperature, and downslope water movement. These data are required over a spatial grid meshed at resolutions typically in the range of 10 - 100 m. Previous studies have found hydrologic models to be sensitive to the horizontal resolution of DEMs resulting from the influence of horizontal resolution on the computed slope and hydrologic fluxes (Zhang and Montgomery, 1991; Wolock and Price, 1994). The quality of elevation data from "non-standard" sources, space and airborne sensors such as radar and laser altimetry, brings into question how the vertical accuracy of these data will affect hydrologic predictions.

1.1 Objectives

The objectives of this thesis are:

- a) to determine how the vertical accuracy of DEMs affect spatial and temporal predictions of runoff and hydrological fluxes;
- b) to compare DEMs from different sources to determine the spatial structure of differences in elevation and derived topographic parameters;
- c) to assess the viability of a spaceborne, interferometric-based DEM for hydrological modeling.

1.2 Approach

Three DEMs and resulting hydrologic model predictions were examined for the study site. The high resolution product is a 5 m DEM produced by Photo Sciences, under contract to Pennsylvania State University from low altitude aerial photography. The 5 m data were resampled to a 30 m resolution using a method that preserved the spatial structure of the elevations and gradients. The resulting 30 m DEM is used as the reference for comparison with two DEMs from other sources. The standard 30 m USGS 7.5' DEM and a third DEM produced by NASA/Jet Propulsion Laboratory (JPL) using interferometric processing of a pair of Spaceborne Imaging Radar-C (SIR-C) images (30 m) were compared to the reference product both in terms of directly derived quantities such as elevation differences, slope, and contributing area and indirectly through comparative evaluation of hydrologic modeling results.

Vertical errors were calculated as the difference of the USGS and SIR-C DEMs from the reference elevations. The spatial structure of the difference images were examined and systematic errors in the USGS DEM were evaluated by comparison of derived topographic parameters in light of information provided by the USGS about the DEM production process.

The Distributed Hydrology-Soils-Vegetation Model (DHSVM), is a spatially distributed, physically based hydrologic model (Wigmosta et al, 1994). It was calibrated to the Mahantango Creek

Experimental watershed as defined by the reference DEM and was used to simulate watershed conditions, state of the water table (soil moisture and depth to water table) and spatial distribution of fluxes (runoff, evapotranspiration) for a four year period using each DEM. The resulting runoff time-series and spatially distributed hydrological fluxes were compared to determine how the vertical accuracy of the topographic data affected model predictions.

1.3 Digital elevation models

Digital Terrain Models (DTMs) are ordered arrays that represent the spatial distribution of terrain attributes. Digital Elevation Models (DEMs) are a subset of DTMs that represent the spatial distribution of elevation, and hence define a topographic surface. The elevation data can be structured as a) regularly-spaced rectangular or angular grids, b) triangular irregular networks, or c) contour-based networks. The three representations are shown schematically in Figure 1.

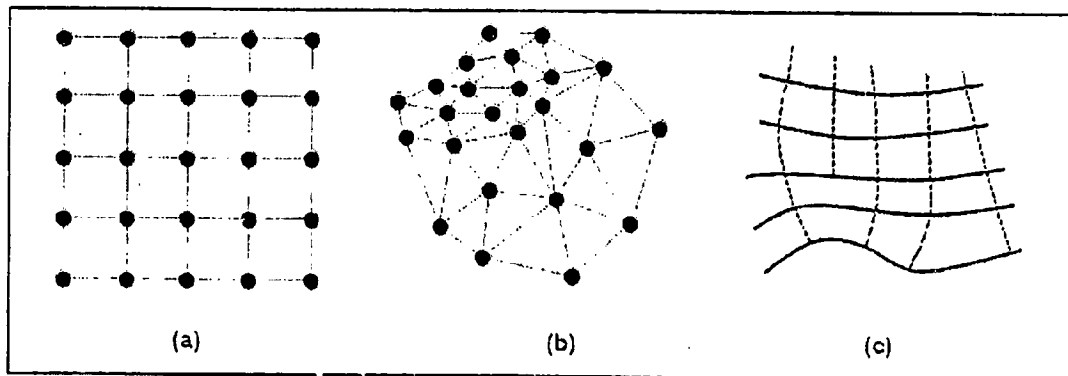


Figure 1. DEM network structure (adapted from Moore et al, 1991)

Triangular Irregular Networks (TINs) are stored as sets of x, y, and z coordinates taken at "surface-specific" locations where there are abrupt changes of slope. The neighbors of each point are also designated and the resulting surface is modeled as a set of contiguous non-overlapping triangular facets with vertices of known elevation. TINs have the advantage of representing geomorphic features with a minimum of points by retaining only the topographically relevant features. However, each point requires

the storage of the three spatial coordinates and six pointers. Pointers are required either from each sample point to all linked points or from each triangular element its three vertices and three adjacent triangles (Palacios-Velez and Cuevas-Renaud, 1986).

Contour-based networks are formed from digitized contour lines and are stored in vector form as digital line graphs (DLGs). Data are given as x, y coordinates along contour lines of specified elevation. The resulting surface is formed of irregular polygons bounded by adjacent contour lines and the orthogonal streamlines. Contour-based networks require a large amount of data storage in order to capture the non-linear behavior of the contours. From a hydrological standpoint, they are most advantageous in cases where overland flow is important, e.g. in urban areas, as contours represent equi-potential lines and the orthogonal streamlines are no flow boundaries.

Grid-based networks use a regularly-spaced triangular, rectangular or angular grids. The most widely used structures are square-grid networks in degrees (latitude and longitude) or in linear dimensions. Grid sizes range from less than 10 meters with availability for small areas, up to 10 km data, which are available globally. Grid-based networks have the disadvantage of not capturing features in the terrain that occur between grid points. This results in a loss of information as abrupt changes in elevation can not be well represented, nor can upslope flow paths that are not smooth be well represented. Further, it is difficult to determine the specific contributing area when it is not much larger than the grid cell area. A higher horizontal grid resolution reduces the impact of these problems but results in additional computational time and redundancies in areas of smoother terrain (Moore et al, 1991). Square grids are more computationally efficient and easier to implement than TINs and contour-based networks and have become the standard for data distribution and in hydrologic modeling. They are, therefore, the focus of this study.

1.3.1 Standard DEM sources

Digital elevation data for the United States are produced by the U.S. Geological Survey (USGS) as part of the National Mapping Program (USGS, 1993). USGS DEMs are available in several standard formats:

- a) 30 m horizontal resolution square grid cast on a Universal Transverse Mercator (UTM) projection which covers a standard USGS 7.5 minute map series quadrangle
- b) 3 arc-second angular grid which provides coverage of a 1 by 1 degree geographical block
- c) 30 arc-second angular grid Digital Chart of the World (DCW) data

The 30 m resolution, 7.5 minute UTM DEMs are available for selected quadrangles, which are indicated on a graph published biannually by USGS. These data are currently available for about 70% of the conterminous U.S. and are used in hydrologic models of small to moderate size catchments. Digital elevation data are classified as Level 1, 2 or 3 depending on the data source, with Level 3 being the most accurate. Approximately 50% of the available DEMs are classified as Level 1, which are derived from automated or manual scanning of National High-Altitude Photography Program (NHAP) photographs (1:80,000 scale). The remaining DEMs are classified as Level 2 and are derived from digitizing map contour overlays (1:24,000 scale USGS quadrangle maps). Level 3 data are available only for some experimental watersheds (<1% of available DEMs) and are derived from automated scanning of National Aerial Photograph Program (NAPP) photographs.

3 arc-second DEMs for 1 by 1 degree blocks are available for all of the contiguous United States, Hawaii, and portions of Alaska, Puerto Rico, and the Virgin Islands. These data are most appropriate for hydrological modeling of 100 to 1000 km² catchments. Elevations are derived either from cartographic or photographic sources (1:24,000 - 1:250,000 scale). Elevations from photographic sources are derived by manual and automated correlation techniques. Elevations from cartographic sources are derived by processing digitized hypsographic features into the required matrix form and interval spacing. The 3 arc-

second production process is similar to that of the 30 m, 7.5 minute DEMs but at a coarser scale and lower resolution. The available higher resolution 30 m, 7.5 minute DEMs have been aggregated to a 3 arc-second resolution through a cooperative project between the USGS and the U.S. Defense Mapping Agency but these DEMs are currently not available to the general public.

30 arc-second DEMs with global coverage are currently being produced by the U.S. Geological Survey's Earth Resources Observation Systems (EROS) Data Center (USGS, 1996a). North America, Africa, Japan, Madagascar and Haiti are complete and available to the public by anonymous ftp; data sets for South America, Europe and Asia are under development. These data are most appropriate for macro-scale models. Applications include automated estimation of drainage networks at the continental scale (Miller and Russell, 1992) and estimation of sub-grid variation in elevation for orographic precipitation models (Leung and Ghan, 1995). Elevation data are derived primarily from the Defense Mapping Agency 1:1,000,000 scale Digital Chart of the World (DCW) contour and hydrology data. The Australian National University Digital Elevation Model (ANUDEM) was used to reconcile the DCW hydrographic information and hypsography to generate a hydrologically realistic DEM (Hutchinson, 1989). The North American DEM was derived by aggregating 3 arc-second DEMs to the desired 30 arc-second resolution.

1.3.2 Higher resolution DEMs

Higher resolution DEMs can sometimes be obtained for specific watersheds. These are developed as needed and the production and resolution of the digital elevation data are determined by the imagery available for the site.

For some experimental watersheds, aerial photography has been obtained from low altitude flights flown specifically for the purpose of collecting topographic information. Stereo-correlation photogrammetric methods can be applied to these data to produce DEMs of much higher vertical accuracy than models based on the high altitude flights of the National Mapping Program used in the standard USGS DEMs. These DEMs have the advantage of being of high vertical and horizontal resolution. The

low altitude photography must be obtained and processed into a DEM on a site specific basis, which is both costly and time-consuming.

Some experimental work has been done on construction of DEMs from satellite imagery. The European earth-observing satellite system, Satellite Pour l'Observation de la Terre (SPOT), produces stereo pairs from the parallax created by combining two images of the same area acquired on different dates. DEMs have been constructed directly from this imagery using automatic stereo-correlation, similar to the processing of manual photogrammetry. SPOT 3 is currently in orbit and will be followed by SPOT 4 which is scheduled for launching in late 1997. Most recent work has been in the development of SPOT 5 to be launched late in 2001. The specifications of SPOT 5 call for a planimetric accuracy of 10 m and an elevation accuracy of 5 m. This accuracy is compatible with conventional mapping standards at 1:50,000 scale (USGS, 1996b). Satellite imagery has the advantage of being readily available for large areas.

Aircraft and spaceborne radar imagery are currently being explored as a replacement for traditional aerial photography. Radar measures the strength and return time of microwave signals that are emitted by a radar antenna and reflected off a distant surface or object. The length of the radar antenna determines the resolution of the image in the flight direction. The longer the antenna, the finer the resolution in this direction. Synthetic Aperture Radar (SAR) refers to a technique used to synthesize a very long antenna by combining echoes received by the radar as it moves along its flight track. SAR is particularly applicable to airborne and spacecraft applications where the physical dimensions of the antennae are constrained. DEM accuracy is dependent on the navigational accuracy of the flight. Radar has the advantage that it can be used to map areas inaccessible to aerial photography due to darkness or adverse weather conditions.

Interferometric methods can be used to obtain accurate measurements of wavelengths for precise length measurements. The interferometer splits an electromagnetic beam into two parts and recombines them to form an interference pattern after they have traveled over different paths. The National Aeronautics and Space Administration, Jet Propulsion Laboratory (NASA/ JPL) has developed an aircraft

radar interferometer, Topographic Synthetic Aperture Radar (TOPSAR), that uses a synthetic aperture radar and interferometry to produce topographic maps rapidly. Interferometric TOPSAR surface maps are constructed by comparing the phase differences between radar images from two antennae mounted nearly vertically on the left side of a NASA DC-8 aircraft (Zebker et al, 1992). Elevation errors for the TOPSAR system range from 1 to 3 meters with a horizontal resolution of 5 to 10 meters.

The Spaceborne Imaging Radar-C/X-band Synthetic Aperture Radar (SIR-C/X-SAR) is an imaging radar system developed as a joint project of NASA, the German Space Agency (DARA) and the Italian Space Agency (ASI). X-SAR provides single frequency, single polarization (vertical) data, while SIR-C provides multi-frequency, multi-polarization radar data. Interferometric methods can be used to create topographic maps from the SIR-C data over very large areas. The system was flown aboard the NASA space shuttle Endeavor on flight SRL-1, shuttle mission STS-59, April 9 - 20, 1994, and flight SRL-2, shuttle mission STS-68, September 30 - October 11, 1994. An additional flight is currently being scheduled with the intention of covering 80% of the earth's surface (-60° to $+60^{\circ}$ latitude) in 11 days. Elevation errors for the SIR-C/X-SAR system range from 8 to 10 meters with a horizontal resolution of 30 meters.

TOPSAR and SIR-C/X-SAR observations are a precursor for a possible earth-orbiting SAR mounted on a satellite. One proposal, Topographic Satellite (TOPSAT), calls for two nearly identical spacecraft that would be launched and operated in tandem. The L-band (25 cm wavelength) radar system on the TOPSAT satellites would be able to acquire a global topographic map of the earth with height resolution of 2 to 5 meters for ground resolution pixels with sizes of 30 meters. Research is currently being directed towards developing a physically smaller, low power system with an inflatable antennae in the Advanced Radar Technology Program (ARTP SAR). This smaller system would be less costly than the proposal for two TOPSAT spacecrafts.

Radar altimetry mounted on board satellites such as U.S. Navy Geodetic Satellite (GEOSAT), European Remote-Sensing Satellites (ERS-1 and ERS-2) and NASA/ JPL Ocean Topography Experiment

(TOPEX)/Poseidon have been used to measure sea surface elevations (DEOS, 1996). The altimeter sends radar signals to ocean surfaces and collects the return pulse. The returned power as a function of travel time is called the waveform and provides information on the height of the satellite above the surface. Combined with a precisely computed orbital altitude, this gives the surface elevation above a well-defined geocentric reference frame. TOPEX/Poseidon is the most recent altimeter carrying satellite and is equipped with two experimental altimeters, one French and one American. The U.S.-made altimeter measures the sea surface with an accuracy claimed to be 2 cm. Measurements over water are much more accurate than over land which has the complication of vegetation coverage and differing soil types. Current applications are focused on measurements of the ocean surface and gravity anomalies but, with improving technology, satellite altimetry may be used to collect digital elevation data over land if the influence of vegetation and other surface coverage can be eliminated.

Laser altimeter systems have recently been developed to provide high-resolution, geo-located measurements of vegetation vertical structure and ground elevations beneath dense canopies. These systems can provide sub-meter accuracy measurements of earth surface topography at spatial sampling scales as small as 1 m, and typically in the 2 - 15 m range. The Scanning Lidar Imager of Canopies by Echo Recovery (SLICER) developed by NASA is one example of airborne laser altimetry (Blair and Harding, 1996). SLICER is capable of measuring both the round-trip travel time of individual laser pulses and the back-scattered laser "echoes" that are received by the altimeter. A waveform results from the reflection of a single laser pulse from multiple targets at varying heights, including returns from the highest elements of the canopy and from the ground. The waveform is digitized to provide a measure of the vertical distribution of vegetation surface area and the underlying ground's height distribution introduced by surface slope and roughness. Images are collected continuously along the flight track at a width of 20 laser beams, each of 10 - 15 m diameter. The laser footprints are geo-located by combining the laser ranging data with aircraft position, obtained from a differential kinematic Global Positioning System (GPS) trajectory, and laser pointing knowledge, obtained from an Inertial Navigation System. This

technology is currently only applicable to small study areas (typically the swath width is ~200m). It could be used as a control within a larger area when combined with elevation data from other sources.

1.4 Hydrologic modeling

Hydrologic models attempt to describe the response of a watershed to precipitation and all forms of energy input. Models differ in the way they represent the physical processes of the hydrologic cycle and the watershed characteristics, both spatially and temporally. Physical processes may be represented empirically, conceptually or explicitly. This latter modeling approach is referred to as physically based. Lumped models treat the watershed as one or more homogeneous land segments whereas distributed models explicitly represent spatial variability by dividing the watershed into a grid and modeling each grid cell individually. Models which maintain a water balance over the catchment at each time step can be used to simulate continuously over long periods of time, whereas event models simulate individual single events and require specification of initial conditions for each event.

Major developments in hydrologic modeling began in the 1960's as the advent of digital computers made hydrologic simulation computationally feasible. Earlier models were concerned with predicting water quantities, such as runoff volumes and discharges, at a catchment outlet. Models were predominantly lumped and did not address the spatial variability of hydrologic processes and catchment parameters (Moore et al, 1991).

The Stanford Watershed Model (SWM) was one of the earliest hydrologic models. It is a conceptual, lumped, continuous model. The basin may be divided into sub-areas which are simulated separately. The responses of each sub-area are combined to determine the outflow from the entire catchment. This allows some representation of spatial variations within the basin. The water quantity routines in SWM evolved into the Hydrologic Simulation Package FORTRAN (HSPF) which is maintained and distributed by the U. S. Environmental Protection Agency (EPA).

The rising popularity of water quality models in the 1970's required the ability to simulate sediment and nutrient transport within landscapes. Surface and subsurface flow characteristics, such as flow depth and velocity, are the driving mechanisms in transport models. Lumped models which do not consider the effects of topography on the hydrologic process are unable to define the spatial variability of these parameters adequately (Moore et al, 1991). Recent grid-based hydrologic models, such as the Systeme Hydrologique Europeen model (SHE) and the Distributed Soil-Hydrology-Vegetation Model (DHSVM), attempt to provide this information by using digital elevation data and spatial definitions of catchment characteristics, such as vegetation and soil type, to simulate spatially varying hydrologic processes. The response of each grid cell is simulated and then aggregated by routing flow from element to element. Behaviour within each grid cell is assumed to be homogenous.

Some spatially distributed models reduce computational demands by simplifying the definitions of the hydrologic processes. TOPOG is an example of a conceptual, distributed model which simulates saturated area based on a steady state drainage condition (O'Loughlin, 1986). Indexing can also be used to avoid the complexities of a fully distributed model. Spatial variability of soil moisture is represented by the distribution function of some parameters, referred to as an index, while other parameters are lumped as a single homogeneous value (Moore and Hutchinson, 1991). The best known indexing scheme is the topographic index used by TOPMODEL (Beven and Kirkby, 1979) which results from certain assumptions, notably quasi-steady flow in the saturated zone. Because TOPMODEL has been so widely used, a brief overview is provided in the following section.

1.4.1 TOPMODEL

TOPMODEL (Beven and Kirkby, 1979) is a topographically based model which uses the probability distribution of a topographic index to represent the spatial distribution of soil moisture. This model has been widely used in hydrologic studies, including investigations on spatial scale effects, topographic effects on water quality, climate change and identification of hydrologic flow paths.

The topographic index, λ_i , is defined at each grid cell, i , as:

$$\lambda_i = \ln \left(\frac{a_i}{T_i \tan \beta_i} \right) \quad (1)$$

where a is the upslope contributing area, per unit contour length, to a grid cell, T is the soil transmissivity and $\tan \beta$ is the local slope angle. The index represents the tendency of flow to accumulate at any point (in terms of a) and the tendency for gravitational forces to move this water downslope (in terms of $\tan \beta$ as an approximate hydraulic gradient). It is used as a basis for the prediction of source areas, saturation excess, overland flow and subsurface flows.

TOPMODEL makes the critical assumption that locations within a catchment with the same topographic index are hydrologically similar. This assumption is based on the relationship between the average depth to the water table, \bar{z} , and a local depth, z_i :

$$z_i - \bar{z} = \frac{1}{f} \left[\lambda - \ln \left(\frac{a T_e}{T_i \tan \beta} \right) \right] \quad (2)$$

where λ is the expected value of the topographic index for the catchment, T_i is the soil transmissivity and $\ln(T_e)$ is the spatial average of $\ln(T_i)$. If the variance of the topographic index is greater than that of local transmissivity, then the predicted patterns of water table depths and resulting saturated contributing area are dependent on the topographic index.

TOPMODEL computations are distributed statistically according to the probability distribution of the topographic index. The index is discretized and a water balance is performed for each interval of the distribution. Local water-table depth is computed from the index and modified by capillary fringe effects, evapotranspiration through the root zone, and recharge through the unsaturated zone to give an estimate of the local soil moisture. Predicted hydrographs are composed of a subsurface, lumped saturated response and saturation-excess runoff generated from dynamic source areas. There is no explicit routing of either subsurface or surface flows. Predicted water-table patterns will follow the outline of the topographic index with saturated source areas expanding and contracting as the water balance of the model changes. Since

the topographic index is determined solely by the topography, all variables computed by TOPMODEL can be mapped back to a specific location (Beven and Kirkby, 1979; Quinn et al, 1995).

1.4.2 DHSVM

The Distributed Soil-Hydrology-Vegetation Model (DHSVM) was developed by Wigmosta et al (1994) to provide an integrated representation of hydrology-vegetation dynamics at the topographic scale described by digital elevation data. Unlike TOPMODEL, DHSVM is a distributed, physically based model which models each grid cell individually and explicitly routes subsurface (saturated zone) moisture between cells.

DHSVM maintains a detailed water and energy balance at each node in the grid, using a two-layer canopy model for evapotranspiration, an energy balance model for snow accumulation and melt and a two-layer rooting zone model, with a saturated subsurface flow model which explicitly predicts the lateral distribution of water. Digital elevation data are used to describe topographic controls on meteorological input data and to predict downslope water movement. At each time step, the model provides a simultaneous solution to the energy and water balance equations for every grid cell in the watershed.

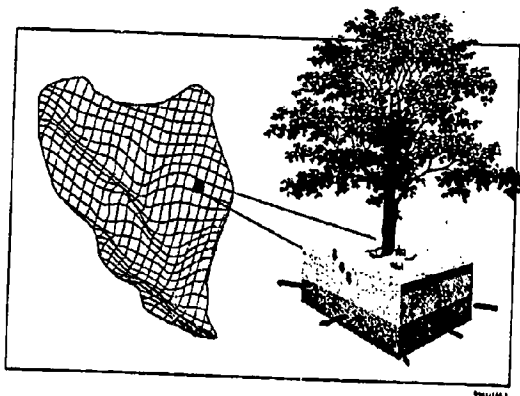


Figure 2. DHSVM representation of a land segment

Topography affects the spatial distribution of short-wave radiation due to the effects of shading, shadowing and reflection from surrounding terrain. The two-stream radiation model of Dubayah et al (1990) is used to predict the topographic effect on incoming solar radiation. Air temperature varies with elevation according to an assumed lapse rate. Precipitation can also be distributed over the basin using either a lapse rate or a more sophisticated orographic model based on air flow over topography.

Surface cover and soil properties are defined for each grid cell. The land surface can consist of overstory vegetation, understory vegetation and soil. The model calculates evaporation and transpiration independently for each vegetation layer. Evaporation of intercepted water is assumed to occur at the potential rate; transpiration from dry vegetative surfaces is calculated using a Penman-Monteith approach. The overstory is allowed to remove water from both the upper and lower soil zones while the understory can only remove water from the upper zone. The overstory and understory canopies attenuate wind speed and solar radiation based on cover density and leaf area index.

Precipitation on each grid cell is partitioned into rain or snow based on air temperature. The snowpack energy balance includes snowmelt, refreezing and changes in the snowpack heat content to compute snow temperature in a 2-layer scheme with a thin surface layer. The snowpack mass balance simulates the volume of liquid water and ice within the snowpack. Water is removed from the snowpack when the liquid phase exceeds the current liquid water storage capacity of the snowpack. The snowpack, if present, is assumed to completely cover both the understory and the soil, and to either completely cover the overstory or remain entirely below it depending on the local vegetation height. Surfaces covered by snow do not contribute evapotranspiration and radiation absorption and reflectance is based on the snow rather than the vegetation.

The soil column is modeled as a two layer rooting zone. The upper layer thickness is equal to the average rooting depth of the understory vegetation; the lower layer extends from the bottom of the upper layer to the average overstory rooting depth. All canopy throughfall and snowmelt enters the soil column where it percolates downward based on Darcy's law. Moisture may leave the soil column due to soil

evaporation (from upper zone only), overstory vegetation transpiration, understory vegetation transpiration (from upper zone only), as saturated subsurface flow, or saturated overland flow. Saturated overland flow is generated when a rising water table reaches the ground surface. In the version of DHSVM used for this study, surface runoff is routed to the basin outlet using the unit hydrograph formulation of Maidment et al (1993). Subsequent changes to the model have introduced an overland routing algorithm which imposes explicit stream channels on the DEM (Bowling et al, 1996; Nijssen et al, 1996b; Perkins et al, 1996).

Grid cells are hydrologically linked to adjacent cells through a quasi-three dimensional saturated sub-surface transport scheme which redistributes soil moisture explicitly on a pixel-by-pixel basis. Water is distributed between adjacent grid cells according to the local hydraulic gradients which are approximated by local ground surface slope slopes as calculated from the digital elevation model. A cell receives water from its upslope neighbors and discharges to its downslope neighbors. The rate of discharge is calculated as the product of the estimated soil transmissivity, ground surface slope between cells, and the width of the flow path.

Wigmosta et al (1994) describe a test application of DHSVM to the 2900 km² Middle Fork Flathead River basin in northwestern Montana. DHSVM has also been applied to the Snoqualmie River watershed in western Washington with modifications that incorporated an orographic model to distribute precipitation, a surface snow layer, a channel routing scheme and revised representation of vegetation affect on aerodynamic resistance under the forest canopy (Storck et al, 1995). Other applications of DHSVM include the Little Naches and Cabin Creek Basins, Washington, for the purpose of predicting the effects of forest harvest on streamflow (Wetherbee and Lettenmaier, 1996).

Detailed observations of moisture and energy fluxes at Boreal Ecosystem-Atmosphere Study (BOREAS) tower flux sites were used by Nijssen et al (1996a) to evaluate DHSVM's ability to model latent and sensible heat fluxes in the 574 km² White Gull Creek catchment located in Manitoba, Canada. Average seasonal heat fluxes and the diurnal cycle in the latent heat fluxes were accurately modeled. A

phase shift was observed in simulated sensible heat and net radiation flux simulation that was attributed to the soil heat flux algorithm which may not be applicable to the Boreal region. An improved soil thermal model is currently being developed to address this issue. Arola and Lettenmaier (1996) compared predictions using DHSVM to point values computed using a macro-scale equivalent model (MSE) to determine the sub-grid effects on energy and moisture fluxes at the GCM (General or Global Circulation Model) scale. Major differences were observed in predictions of snow water equivalent that were attributed to the lack of representation of topographic effects (shading and shadowing) on solar radiation in the MSE.

An on-going application of DHSVM to Hard Creek and Ware Creek, Washington (Bowling et al, 1996) investigates the effects of logging roads on overland flow. For this purpose, an overland flow routing routine has been added to DHSVM. Subsurface flow and precipitation that enters a pixel on the pre-defined stream channels is routed through the channel to the basin outlet using Muskingum routing (Nijssen et al, 1996; Perkins et al, 1996).

1.5 Investigations of the hydrologic effects of DEM resolution

Although the effect of vertical accuracy of DEMs on hydrologic predictions has received relatively little attention, the effects of horizontal resolution have been addressed in some recent studies. For instance, Zhang and Montgomery (1994) examined high resolution contour maps of two small catchments (Mettman Ridge, Oregon, 0.3 km² and Tennessee Valley, California, 1.2 km²) to assess the effect of DEM horizontal resolution on topographic parameters and hydrologic simulation. DEMs of increasing grid size were constructed from the higher resolution data by averaging elevation data within the grid cell. Cumulative frequency distributions of local slope ($\tan \beta$), drainage area per unit contour length (a) and TOPMODEL topographic index, $\ln(a/\tan \beta)$, were calculated based on a steepest descent method which defines the downslope direction according to the orientation of the lowest of the eight neighboring cells. Increasing grid size resulted in a smoothing effect which decreased slopes, increased

contributing areas and increased topographic indexes. Simulations of saturated area with TOPOG, a spatially distributed model based on a steady state drainage condition (O'Loughlin, 1986), predicted increased saturation areas with increased grid size. The index based TOPMODEL (Beven and Kirkby, 1979) predicted increased peak discharges due to the increased topographic index which resulted from increased grid size. A similar study by Wolock and Price (1994) examined 71 areas in Pennsylvania and found that a coarser digital elevation data resolution was associated with higher minimum, mean, variance, and skew values of the $\ln(a/\tan \beta)$ distribution which tended to decrease the mean depth to the water table and increase the ratio of overland flow to total flow and the variance, skew and maximum daily flows predicted by TOPMODEL.

The effects of vertical resolution on geomorphologic parameters used in hydrologic models has been examined by Gyasi-Agyei et al (1995). High resolution DEMs of two natural and two artificial catchments were degraded to lower vertical resolution by successively truncating the last digit of the elevation data up to a vertical resolution of one meter. Geomorphologic parameters were then extracted from all DEMs and compared to determine the effects of the change in vertical resolution. The distributions of the TOPMODEL topographic index did not show any significant differences between the different DEMs although the individual pixel slope, area and topographic index did vary.

2. The Mahantango Experimental Watershed

The WE-38 watershed on Mahantango Creek, Pennsylvania (Figure 3), was chosen as the study site because of the available digital elevation data for this area. WE-38 is a U.S. Department of Agriculture - Agricultural Research Service (USDA - ARS), Northeast Watershed Research Center, experimental watershed located in Klingerstown in eastern Pennsylvania. Records of streamflow, precipitation, and daily maximum and minimum temperature at two meteorological stations date to 1967. Mahantango Creek is within the non-glaciated portion of the Appalachian Ridge and Valley Physiographic Province and is a tributary to the Susquehanna River approximately 50 km north of Harrisburg, PA.

The watershed area is 7.2 km² and rises from 216 to 493 meters with slopes ranging from 0° to 25.6° with a basin average of 7.7°. Land use is 43% cropland, 56% forest and 1% bare surfaces. Forests are located predominantly in the northern ridges and are a mixture of oak, maple, hickory and other hardwoods. Crops rotate between corn, wheat, hay and meadow. There are no urban, industrial or mining areas within the watershed (Pionke and Kunishi, 1992).

The basin climate is temperate and humid. The watershed hydrologic budget was estimated by Pionke et al (1988) based on precipitation and streamflow measurements for 1973 to 1979. The mean annual precipitation is 1128 mm of which evapotranspiration accounts for 479 mm, surface runoff, 229 mm and baseflow, 420 mm. Runoff zones are mostly permanent grass with some pasture. All groundwater discharges to streamflow upstream of the WE-38 weir. The basin is represented by 8000 pixels on a 30 m grid in the DEM.

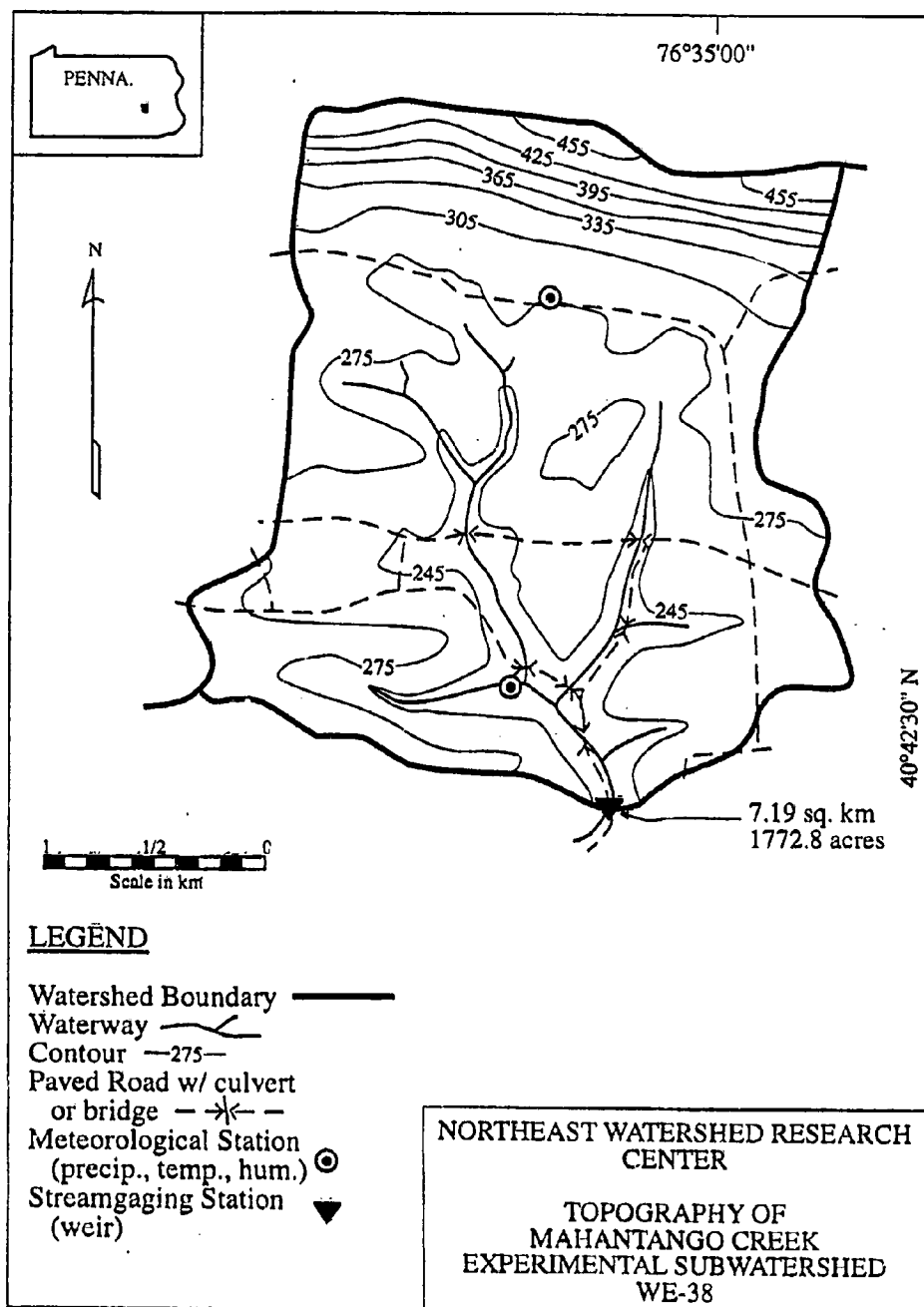
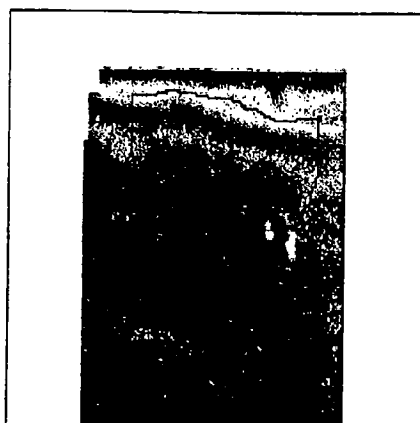


Figure 3. Mahantango Creek experimental sub-watershed, WE-38

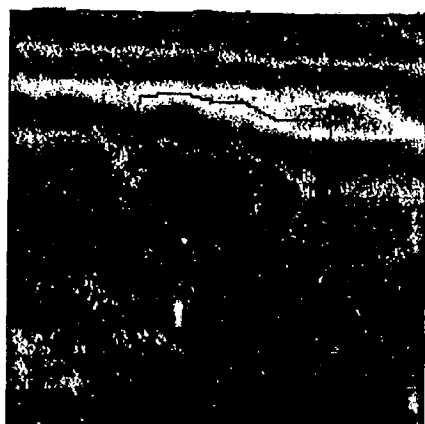
The 420 km² Mahantango Creek Basin encompasses the WE-38 experimental watershed and is the primary research site of the Northeast Watershed Research Center, which has conducted numerous hydrologic investigations there. These studies have examined the hydrology, chemistry and geomorphology of the catchment.

The chemical and hydrologic responses of a 9.9 ha sub-area of the experimental watershed were studied by Pionke et al (1988) to determine the streamflow production mechanisms. They found that during storms, the source area cycles from (1) baseflow-dominated to (2) rainfall diluted baseflow, to (3) surface-runoff-dominated flow, to (4) progressively subsurface-discharge-dominated flow and back to (1) normal base flow in response to changes in seep zone areas and the ratio between surface runoff and seepage. This cyclic behavior was confirmed by an analysis of the chemical characteristics of the streamflow, based on P, PO₄, NO₃ and NH₄ concentrations, which reflected the characteristics of the expected dominant component of the flow. These results supported the variable source area concept which states that most surface runoff occurs from small saturated areas within the watershed where precipitation excess is generated. Source areas include seep zones which were found to be dynamic and readily generated in the Mahantango catchment, expanding substantially and quickly in response to rainfall.



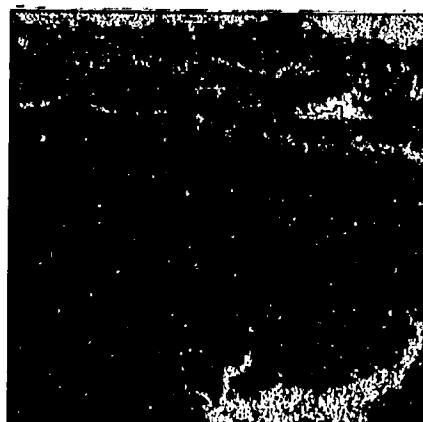
Reference DEM

basin area = 7.20 sq km
average elevation = 286.20 m



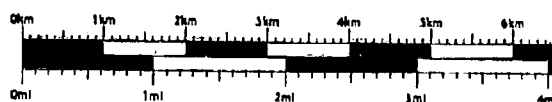
USGS DEM

basin area = 7.20 sq km
average elevation = 293.36 m



SIR-C DEM

basin area = 7.46 sq km
average elevation = 243.43 m



Elevation (m)

Figure 4. Digital Elevation Models of the Mahantango Basin

2.1 High resolution DEM

The high resolution DEM used in this study was developed by Photo Sciences, Inc. under contract to Pennsylvania State University. It was derived from aerial stereophotographs for an area roughly covering the WE-38 intensive study area. The DEM was provided at a horizontal resolution of 5 m, a vertical resolution of 0.1 m with an estimated maximum vertical error of less than 0.5 m. Under closed vegetation canopy, which comprises 56% of catchment area, the vertical error is larger.

The aerial photographs were acquired from flights at 3600 feet above mean terrain on April 21, 1994 at a map scale of 1:4000. Kinematic GPS was used to collect high accuracy horizontal coordinates simultaneously for the center point of each photograph. Nine first order USGS bench marks in the WE-38 area were used as check points. The DEM production process used by Photo Science, Inc. is described as follows based on information provided by Richard White (1996). The photos were used as input to a Zeiss P3 analytical stereo data capture system which scanned the data in sections, creating separate models for each photo pair. Models were selected with UTM northings and eastings at multiples of 5 m and scans were performed along east-west lines separated by 15 m. Elevation values were recorded every 15 m along each scan using automated stereoplotters. Scan lines for some adjacent models were offset by 5 m relative to each other. The data were densified to a 5 m horizontal resolution to construct a common grid, using linear interpolation along each scan line and at right angles to the scan lines. Each data point represents the average grid cell elevation.

This high resolution DEM was downloaded from Pennsylvania State's EOS database (White, 1996). For the present research, the DEM was aggregated from 5 m to a coarser resolution of 30 m to construct a reference DEM that was comparable with the USGS and SIR-C DEMs as described in Section 3.2.

2.2 USGS DEM

The 30 m USGS 7.5' DEM for the Mahantango Creek watershed lies within the Valley View, PA, 7.5' quadrangle, North American Datum of 1927 (NAD-27) (Figure 5). This DEM is classified as Level 1, the least accurate and oldest of the available DEMs. Level 1 DEMs comprise 70 to 80% of current USGS 30 m products. The Valley View DEM was derived from automated scanning of quadrangle-centered photographs using the Gestalt Photo Mapper II (GPM2). The vertical resolution is 1 m with a claimed maximum absolute elevation error of 50 m and a maximum error relative to the surrounding grid cells of 21 m (USGS, 1993).

The GPM2 models are a by-product of an orthophoto production process and were originally created to register the orthophoto maps. The Gestalt Photomapping System is described in detail by Kelly et al (1977) and can be summarized as follows:

- a 47 x 52 regularly distributed grid of points is measured for each 9 x 8 mm area of each photograph, referred to as a patch
- an iterative process is used to scan and correct for parallax at each of the points within the patch
- points are compared to overlapping areas of previous patches (20-50%) to ensure edge-matching
- parallax values are converted to ground heights with corresponding horizontal coordinates
- patches are combined to cover a USGS 7.5' quadrangle and are regridded to the standard format
- DEMs are smoothed to remove any large edge effects

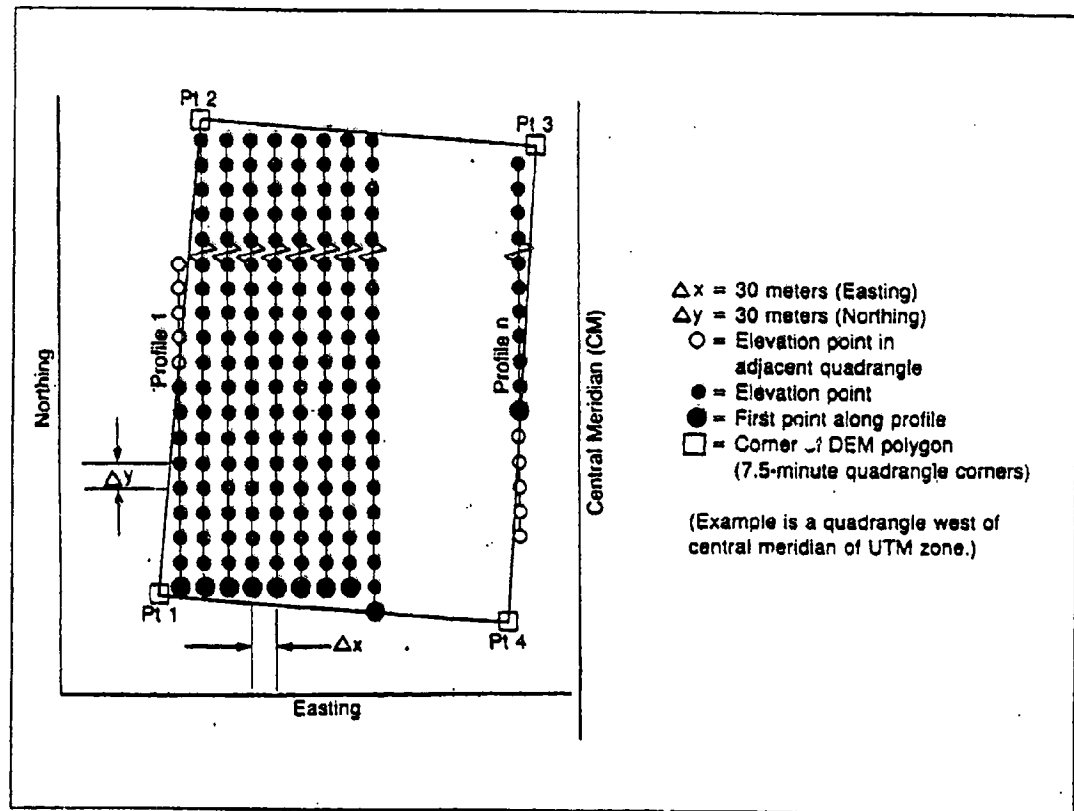


Figure 5. Structure of a 7.5' USGS DEM, 30 m UTM grid (USGS, 1993)

2.3 SIR-C based DEM

A third DEM was provided by Eric Fielding (NASA/JPL) based on a pair of SIR-C images that were collected onboard the NASA space shuttle Endeavor on October 8 & 9, 1994. The shuttle flew at an altitude of 215 km in a circular orbit and a 57 degree inclination. The SIR-C antenna is composed of two planar arrays of radiators for each frequency (L-band, 23.5 cm, and C-band, 5.8 cm). Each array receives vertically- and horizontally-polarized transmitted waves so that images of the magnitude of radar backscatter are acquired in four polarization combinations: HH (Horizontally-transmitted, Horizontally-received), VV (Vertically-transmitted, Vertically-received), HV, and VH.

The average of three polarizations (HH, HV and VV) was used to develop the Mahantango DEM. The use of multiple polarizations reduces the noise in the finished product. Interferometric methods were used by NASA/JPL to process the data using PCI software, a commercial product. Vertical control points were selected from the Mahantango USGS 3 arc-second DEM and the horizontal control points were taken from the 30 m USGS 7.5' DEM. The SIR-C DEM is a preliminary product that was provided for the purposes of this research.

3. Horizontal Aggregation

It was necessary to aggregate the high resolution DEM from a 5 m to 30 m horizontal resolution to create a reference DEM that was comparable with the USGS and SIR-C 30 m DEMs. Several methods were considered for accomplishing the aggregation and these are discussed briefly below.

3.1 Standard methods

The simplest resampling approach is to average the elevations contained within a coarser-grid cell. This method preserves the overall volume of topographic features but suppresses peaks and valleys, resulting in a smoothing effect. The 5 m WE-38 DEM was aggregated by averaging for comparison with other methods.

A more sophisticated method known as envelope orography attempts to reduce the smoothing effect of averaging by adding an increment to the averaged grid elevation. This increment is defined as a constant multiplier of the sub-grid-scale standard deviation of the higher resolution elevation data about their mean. For an idealized two-dimensionally sinusoidal mountain range, an increment of 2.0 times the sub-grid standard deviation will raise the averaged height to the original peak elevation (Wallace et al, 1983). Envelope orography has the advantage of being resolution dependent, i.e. finer horizontal resolutions are associated with smaller increments. While this method captures topographic peaks, low elevation plains and valleys are not well modeled and total orographic volume is not preserved.

3.2 Fractal interpolation scheme

Bindlish and Barros (1996) proposed a modified fractal interpolation scheme to aggregate topographical data while preserving the spatial structure of the elevations and orographic gradients. The 5

m high resolution DEM was aggregated using this scheme as implemented in computer code developed by Bindlish and Barros as follows:

- the topographic data were converted from the spatial domain to frequencies and corresponding amplitudes in the Fourier domain using a Fast Fourier Transform (FFT) algorithm
- the fractal dimension, D , and roughness coefficient of the 5 m data were calculated from the slope and intercept of the log-log plot of the mean power spectral density function respectively, as discussed in Appendix A
- a Brownian random surface was created at a 5 m resolution and transformed to match the fractal dimension and roughness factor of the high resolution DEM
- the transformed Brownian surface was used as a weighting function to aggregate the 5 m DEM to a 30 m resolution
- a correction term based on the standard deviation of the elevations was added to the 30 m DEM

The use of 2D Fourier transforms requires that the data be structured in an $n \times n$ grid of order 2 ($n=2^m$). The extent of such a matrix over the entire research watershed also included areas outside of the watershed where high resolution digital elevation data were not available. Two methods of grid extraction were tested, filled area and piecewise aggregation.

3.2.1 Filled area method

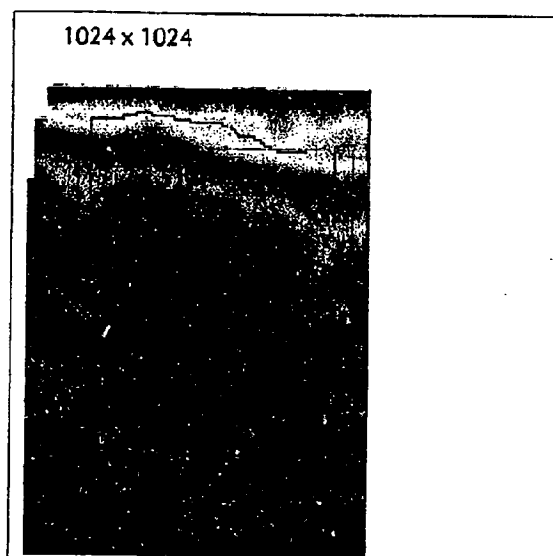
The filled area method aggregated the digital elevation data over the smallest $n \times n$ matrix of order 2 that gave full basin coverage. A 1024×1024 matrix was found to encompass the entire WE-38 watershed. The grid cells within this matrix that were outside the available data were filled with artificial data. Two fill values, zero and the average elevation of the basin, were tested to determine the effect of the selected fill value on the final DEM. The fractal dimension and roughness coefficient were calculated

from the largest matrix of order 2 that would fit within the available digital elevation data, a 512 x 512 pixel area (Figure 6).

Results of the two resamplings were compared to determine effects of the fill value. Elevations varied only at the edges of the DEM coverage area and did not effect elevation data within the basin. A fill value of zero was selected for the final resampling.

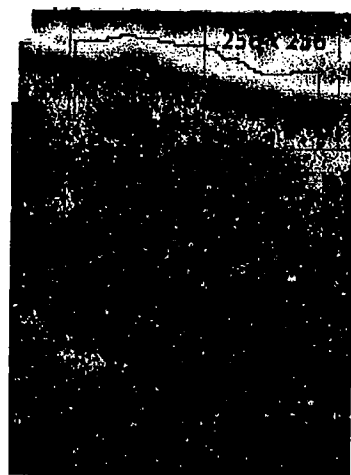
3.2.2 Piecewise aggregation method

An alternative method to filling a large matrix with artificial data was to separate the available digital elevation data into smaller $n \times n$ matrices of order 2. Four 128 x 128 pixel areas and six 256 x 256 pixel areas were required to cover the watershed area (Figure 6). The fractal dimension and roughness coefficient were calculated for each piece from the high resolution digital elevation data and used to aggregate from 5 to 30 meters using the fractal interpolation method. The resulting pieces were joined to produce a DEM that covered the entire watershed.



Filled Area Aggregation

1024 x 1024 area aggregated
with fractal D of 512 x 512



Piecewise Aggregation

each 256x256 and 128x128
segment is aggregated based
on its own fractal D



Elevation (m)

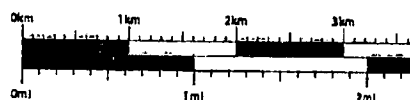


Figure 6. Data Matrices used during fractal aggregation

3.2.3 Sensitivity analysis

The fractal dimension, D , of the data can be calculated by power spectrum analysis. D is determined from the slope of the linear portion of the log-log plot of the power spectral density against the radial wave number (Bindlish and Barros, 1996). The power spectrum for the 512 x 512 pixel sub-area used in the fractal aggregation of high resolution DEM is shown in Figure 7. As the definition of the linear portion of this curve is imprecise, D depends on the interpretation of the spectrum.

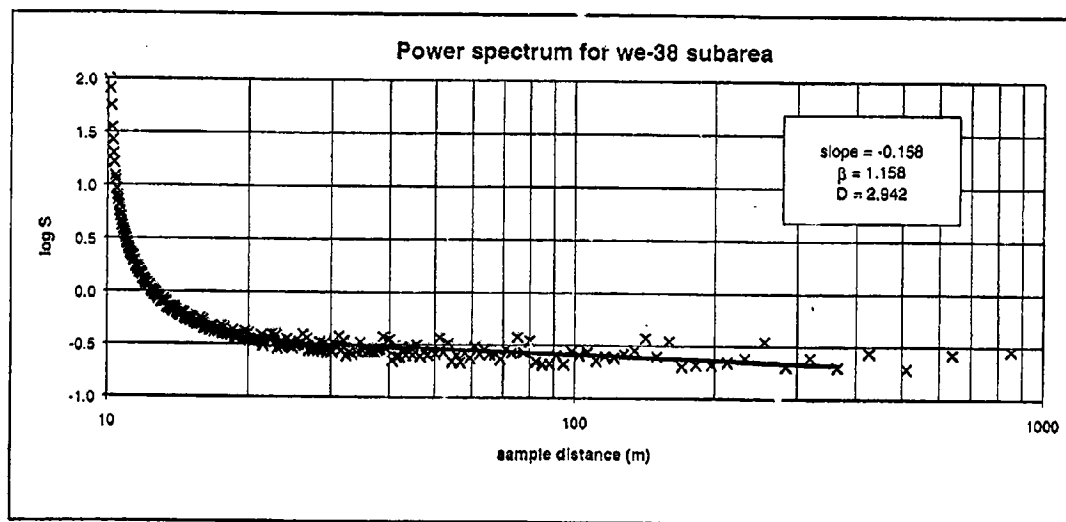


Figure 7. Power spectrum for Mahantango Creek research watershed sub-area

A 256 x 256 pixel sub-area at the southeast corner of the basin was repeatedly resampled to a coarser resolution using a range of fractal dimensions to determine the sensitivity of the fractal interpolation method to this parameter. The high resolution data in this sub-area were found to have a D of 2.785. Data were aggregated using fractal dimensions of 2.0, 2.5, and 3.0. Differences between the aggregated elevations due to the change in D ranged from -0.1 m to +0.1 m, as displayed in Table 1. Larger changes to the fractal dimension resulted in elevation differences in more grid cells although these differences were small (± 0.1 m).

Table 1. Sensitivity of fractal interpolation to fractal dimension, D^1

<i>Fractal Dimension</i>	<i>-0.1 m $\leq \Delta EL \leq 0.0$ m</i>	<i>0.0 m $\leq \Delta EL \leq +0.1$ m</i>
2.0	0.80 % of grid cells	0.63% of grid cells
2.5	0.26% of grid cells	0.28% of grid cells
3.0	0.40% of grid cells	0.55% of grid cells

The roughness coefficient is determined from the value of the power spectral density at a frequency of 1 cycle/pixel and represents the average squared amplitude. Changes to the roughness coefficient result in a raising or lowering of the surface that is used as a weighting function. This does not affect the aggregation of high resolution to a coarser resolution.

3.3 30 m reference DEM

The two methods of applying the fractal interpolation scheme, filled area and piecewise aggregation, gave similar results except at the edges of matrices used in the piecewise method. The edge effect could be reduced by overlapping the segments and discarding the outer portion of each area.

Aggregation using the fractal scheme has the advantage of maintaining the continuity of topography over the basin but may result in some smoothing as local changes in topographic structure may not be captured. The piecewise area approach is more cumbersome and errors in the estimation of the fractal dimension and roughness based on amplitudes and frequencies calculated with FFT algorithm become larger for smaller matrices. For this reason, the filled area method was chosen to aggregate the 5 m high resolution DEM to a 30 m reference DEM for comparison with the USGS and SIR-C 30 m DEMs.

¹ Differences are the aggregated elevation based on the indicated fractal dimension, D , less the results of the resampling with a D of 2.785

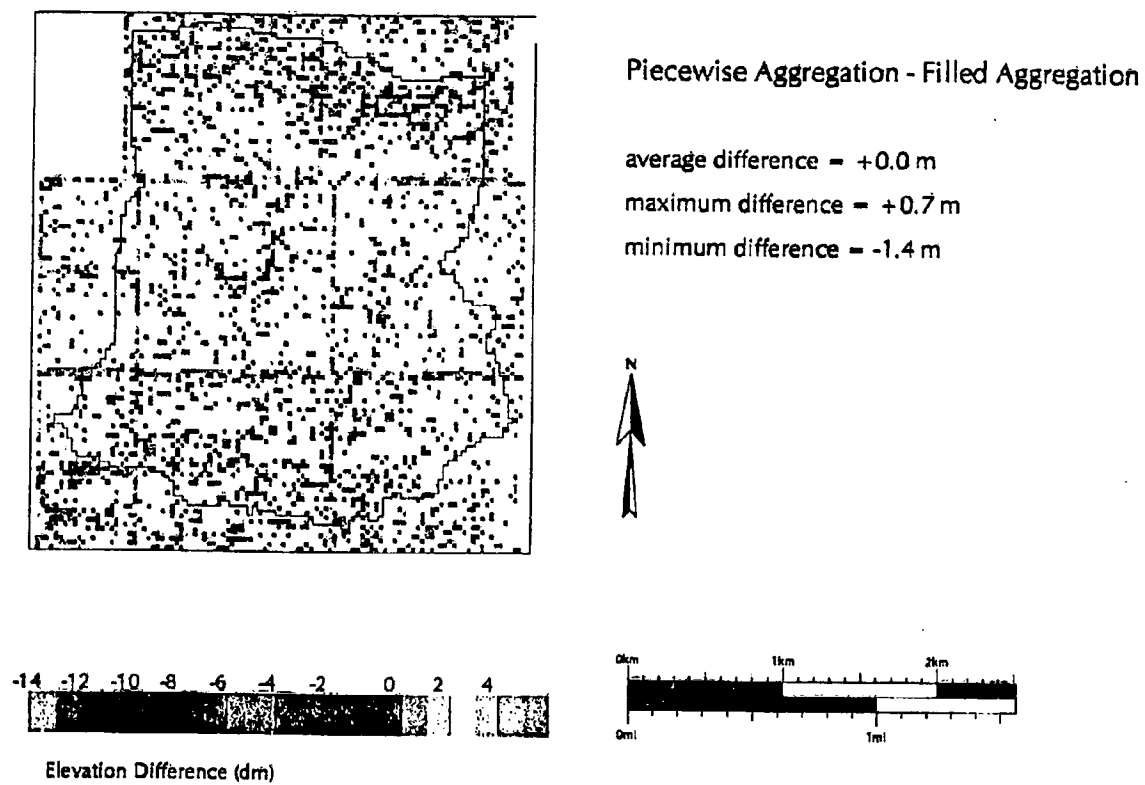


Figure 8. Elevation differences due to fractal aggregation method

4. DEM Comparison

The reference, USGS and SIR-C DEMs were compared to determine the range and nature of their differences. Elevation and elevation-dependent topographic parameters were examined numerically and spatially. A number of programs are available for digital terrain analysis and can be used to calculate basin topographical parameters. The Geographical Resources Analysis Support System (GRASS) of the U.S. Army Construction Engineering Research Laboratories (USACERL) and ARC/INFO, a commercial production available from Environmental Systems Research Institute, Inc. (ESRI) are two such programs.

4.1 Watershed extent and outlet

ARC/INFO algorithms were used to determine the watershed area and the elevation of the basin outlet as defined by each DEM. The DEMs were first checked for pixels which did not drain (sinks), which were eliminated by elevating the sink pixels. DEMs which have been processed to remove sinks are subsequently referred to as "filled" to distinguish them from the raw products. Flow direction and contributing area were also calculated as discussed in Section 4.4.

The outlet of the Mahantango Creek experimental sub-watershed is USDA-ARS weir WE-38, located at 365,856.0 E, 4,507,017.5 N, meters UTM. The outlet in each DEM was selected as the pixel that was closest to the known location of the weir and on the stream channel as represented in the DEM. Outlet and basin average elevations for the SIR-C DEM (Table 2) indicated that the datum for this DEM was apparently inconsistent with the USGS and reference DEM datums. Discussions with Eric Fielding (NASA/JPL) suggested that the vertical datum for the checkpoints used in the SIR-C DEM production (WGS72) does not correctly align with the NAVD29 vertical data used for the USGS DEM. To resolve this difference, all values in the SIR-C DEM were elevated by 50.5 m, the difference in basin outlet elevation between the SIR-C and reference DEMs.

The filled USGS DEM and the filled and elevated SIR-C DEM were used for all subsequent DEM comparisons with the reference DEM and for the hydrologic simulations.

For each DEM, drainage area was determined as the contributing area upstream of the outlet. For the USGS and reference DEMs, the drainage areas agreed to within 0.04%. The SIR-C DEM resulted in a 3.6% larger drainage area than the reference DEM.

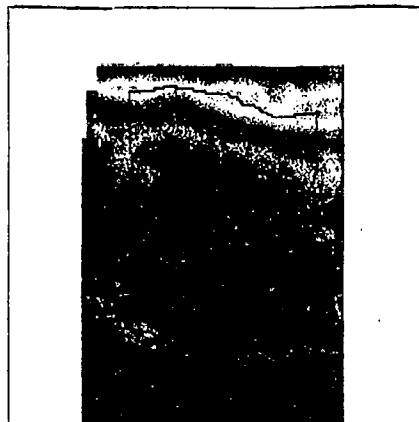
Table 2. Watershed area and elevation

	<i>Reference DEM</i>	<i>USGS DEM²</i>	<i>SIR-C DEM¹</i>
Drainage Area	7.20 km ²	7.20 km ²	7.46 km ²
Sinks Filled	5 pixels	110 pixels	358 pixels
Outlet Elevation	215.9 m	238.0 m	215.9 m
Average Elevation	286.2 m	293.7 m	294.3

Visual inspection of the DEMs reveals deficiencies in the USGS and SIR-C DEMs (Figure 9). The reference DEM produces a sharp image that clearly defines the valley network whereas the USGS and SIR-C images at the same 30 m resolution appear more scattered. The watershed boundaries differ considerably between the three images, becoming more irregular as the vertical resolution decreases. The basin delineation differs the most on the east side of the basin where a sharp notch in the USGS and SIR-C DEMs appears as a round bay-like shape on the reference DEM.

² Values are based on the filled USGS DEM

¹ Values are based on the filled and elevated (+50.5 m) SIR-C DEM

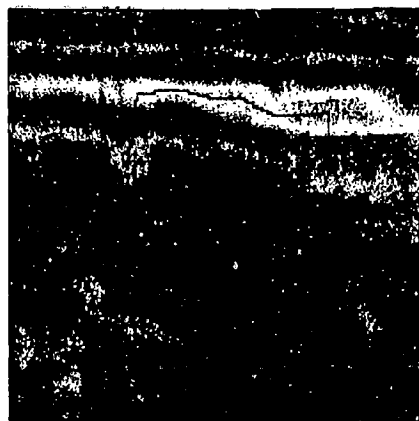


Reference DEM

basin area = 7.20 sq km

average elevation = 286.2 m

outlet elevation = 215.9 m



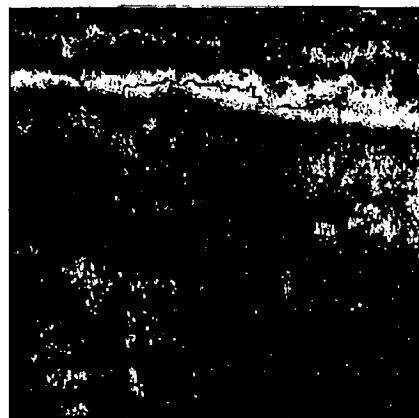
Filled USGS DEM

basin area = 7.20 sq km

110 sink pixels filled

average elevation = 293.7 m

outlet elevation = 238.0 m



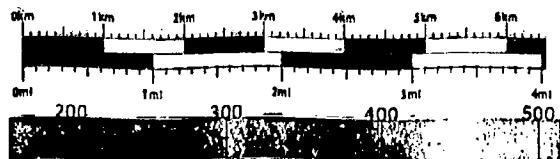
Filled & Elevated SIR-C DEM

basin area = 7.46 sq km

358 sink pixels filled

average elevation = 294.3 m

outlet elevation = 215.9 m (forced)



Elevation (m)

Figure 9. Adjusted Digital Elevation Models

4.2 Elevation check points

Nine check points were acquired from the WE-38 study area to obtain an estimate of the point elevation error of the DEMs. The horizontal positions of the check points were established with GPS by Eric Warner (Pennsylvania State University), using a Trimble receiver and differential correction with data from an established base station. This permitted an x, y accuracy of approximately 2.5 m.

Vertical elevations at the check points were surveyed with a Sokkia Set 4BII total station (Warner and Troutman, 1996). The station uses an active ranging system between the generating source at the station and the prism located above the point of interest. The system can theoretically determine elevation differences of less than 0.01 m. The elevation measurement for the ground control is limited by the quality of the USGS benchmark elevations used as initial points. These benchmarks are accurate to about 0.1 m in the vertical.

Table 3. Check point descriptions (taken from Warner and Troutman, 1996)

<i>Point</i>	<i>Easting m UTM</i>	<i>Northing m UTM</i>	<i>Description</i>
1	365921.8	4507831.3	gully North of Y
2	365774.5	4507102.1	driveway near weir
3	365479.1	4507193.6	near trees on hill
4	366777.1	4507760.9	North power pole
5	365369.2	4509311.2	West of Line Mt. Rd Y
6	364453.9	4509517.9	North West corner, Tree line
7	365675.1	4507427.3	Y intersection
8	366779.3	4507661.3	South pole
9	366364.4	4509095.5	Line Mt. Rd Y

Table 4. Check point elevations

<i>Point</i>	<i>Surveyed elevation⁴</i> <i>(m)</i>	<i>High-resolution</i> <i>5 m DEM</i>	<i>Reference</i> <i>30 m DEM</i>	<i>USGS</i> <i>filled</i>	<i>SIR-C</i> <i>filled and elevated</i>
1	232.03	232.3	231.8	238	236.1
2	223.37	222.9	224.0	238	225.5
3	266.60	267.0	264.3	267	242.7
4	260.20	259.3	259.4	263	270.2
5	282.36	282.7	281.4	282	272.1
6	284.12	297.2	297.1	306	300.8
7	225.94	229.1	227.5	238	241.8
8	268.35	268.2	269.6	270	283.3
9	283.77	283.9	283.4	285	290.5

Differences between the surveyed elevations and those in the corresponding grid cell of each DEM are displayed in Table 5. Elevations are within 1.0 m of the WE-38 5m DEM except for points 6 and 7. Point 6 was located at the tree line and errors may be due to photogrammetric difficulties in determining the ground elevation next to the canopy. Point 7 was on a roadway and should not have been difficult to locate.

The 5 m DEM is more accurate when compared to point elevations than the coarser resolution DEM although the errors are only slightly larger for the reference DEM as compared to the 5m high resolution product. The reference digital elevation data are significantly closer to point elevations than either the USGS or the SIR-C DEMs.

⁴ Check point elevations taken from Warner and Troutman, 1996.

Table 5. Elevation differences in meters at check points

<i>Point</i>	<i>Surveyed Elevation (m)</i>	<i>High resolution 5 m DEM</i>	<i>Reference 30 m DEM</i>	<i>USGS filled</i>	<i>SIR-C filled and elevated</i>
1	232.03	0.3	-0.2	6.0	4.1
2	223.37	-0.5	0.6	14.6	2.1
3	266.60	0.4	-2.3	0.4	-23.9
4	260.20	-0.9	-0.8	2.8	10.0
5	282.36	0.3	-1.0	-0.4	-10.3
6	284.12	13.1	13.0	21.9	16.7
7	225.94	3.2	1.6	12.1	15.9
8	268.35	-0.2	1.3	1.6	15.0
9	283.77	0.1	-0.4	1.2	6.7
	<i>mean absolute difference</i>	2.1	2.3	6.8	11.6
	<i>mean difference</i>	1.8	1.3	6.7	4.0
	<i>standard deviation</i>	4.4	4.5	7.8	13.5

4.3 Spatial Elevation Differences

Elevation differences were calculated between the reference DEM and either the USGS DEM or the SIR-C DEM on a pixel-by-pixel basis. It is assumed in this study that the reference DEM is representative of the true elevations on the watershed and that the differences are due to the errors in the lower accuracy products. Differences are displayed spatially in Figure 11 and as frequency distributions in Figure 12 and Figure 13. The range of SIR-C differences was greater than those of the USGS DEM. The mean difference was lower but this is artificial as the SIR-C elevations were forced to agree with reference

DEM at the basin outlet. The USGS differences display a spatial pattern which is investigated in detail in Section 5.

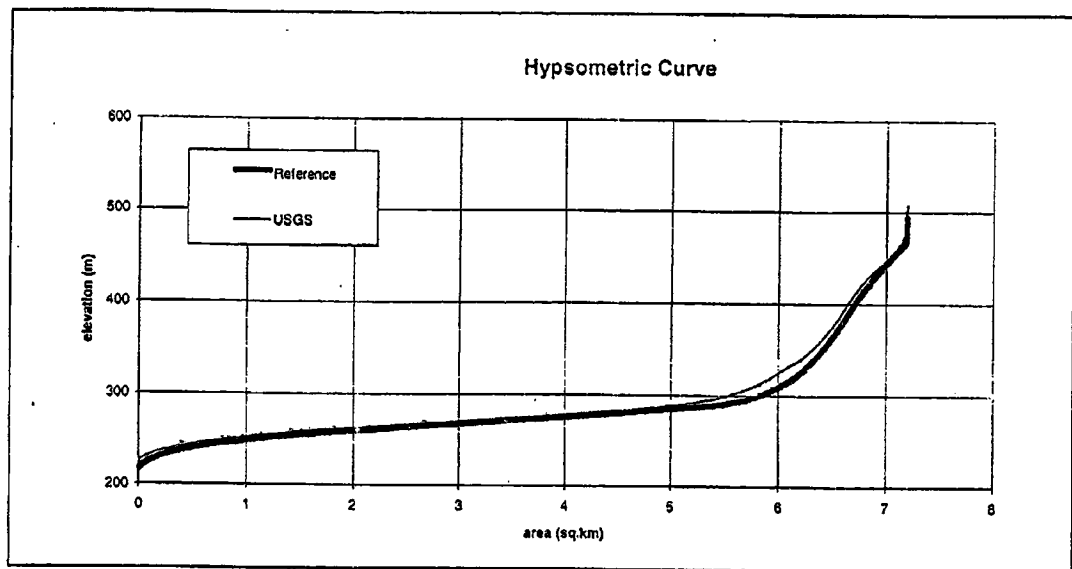
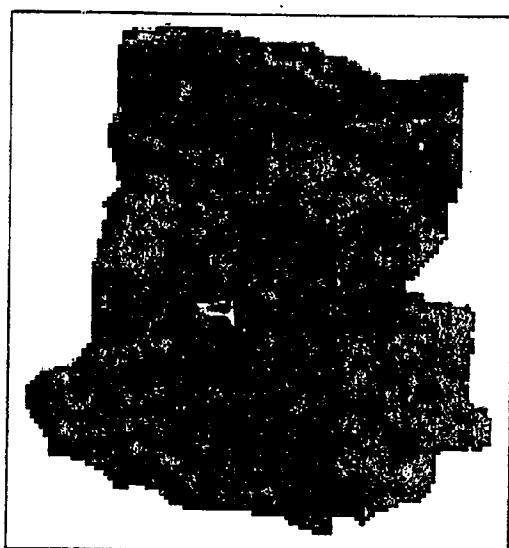


Figure 10. Mahantango basin hypsography

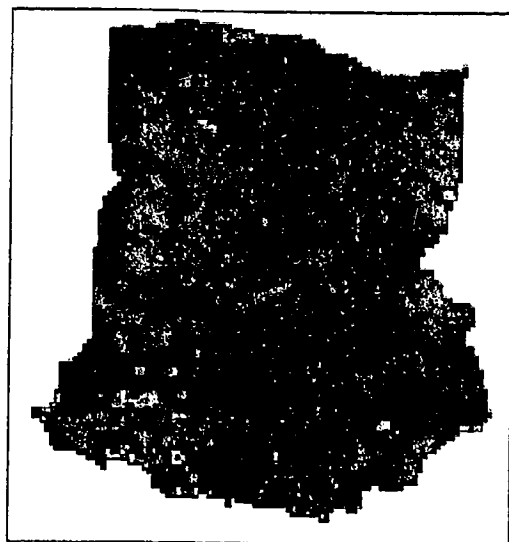


Filled USGS - Reference

average difference = +6.0 m

maximum difference = +27.0 m

minimum difference = -22.1 m

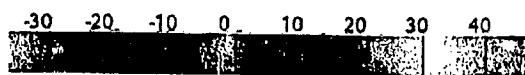


Filled & Elevated SIR-C - Reference

average difference = +1.0 m

maximum difference = +48.1 m

minimum difference = -34.3 m



Elevation Difference (m)



Figure 11. Spatial distribution of elevation difference

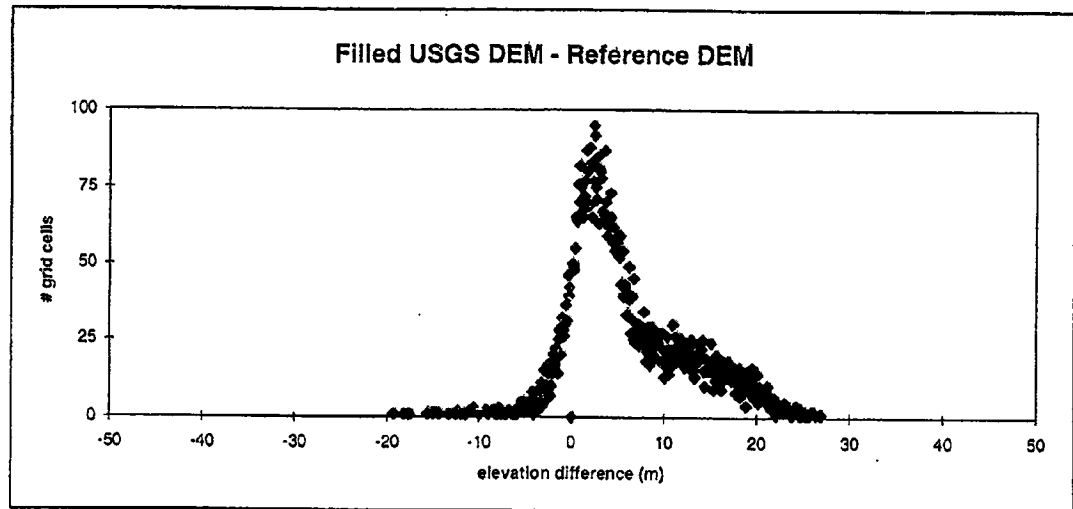


Figure 12. USGS elevation differences

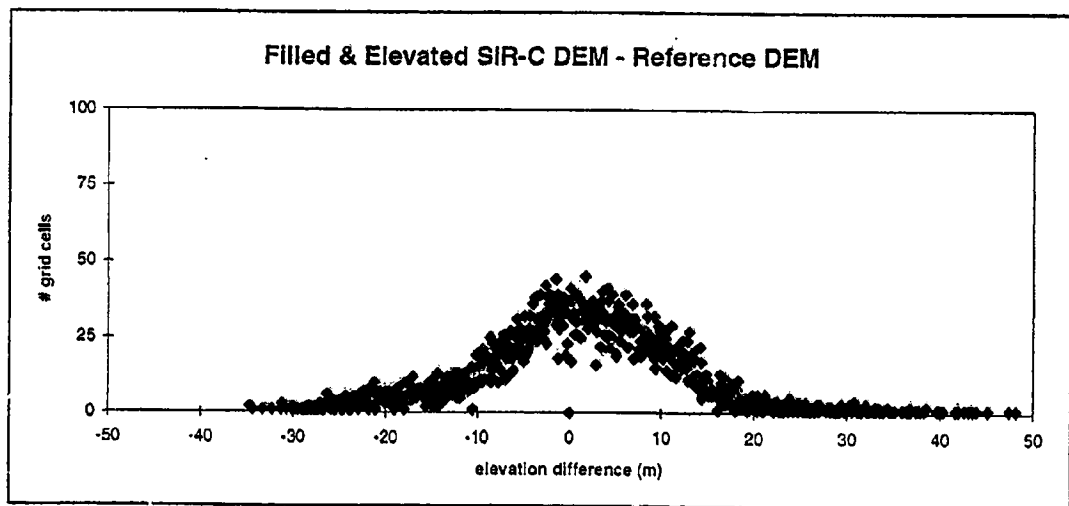


Figure 13. SIR-C elevation differences

4.4 Topographic Parameters

Topographical attributes such as slope, aspect, specific catchment area (upslope area draining across a unit width of contour), aspect, flow path length and profile curvature can be calculated directly from the DEM or from a surface fitted to the point elevation data. The TOPMODEL topographic index (see Section 1.4.1) was calculated from the elevations as it combines slope and drainage patterns, and is related to hydrological behavior.

Many algorithms have been suggested to calculate slope and contributing area. These methods can result in substantially different spatial and statistical distributions. Contributing area depends on the direction of flow from each pixel. Single flow direction algorithms distribute flow from each pixel to one of the eight adjacent cells, usually selected by the steepest descent method which directs flow to the lowest neighbor. Quinn et al (1991) suggested a multiple direction algorithm which weights the distribution of flow between all adjacent, downslope cells by the gradient of each downhill flow path and contour length. A more detailed approach, suggested by Costa-Cabral and Burges (1994), traces the two dimensional, aspect driven flow over the surface. If a flow line enters a pixel then all cells it has previously passed through are defined to be topographically upstream from the pixel and are included in calculation of the total contributing area to the pixel.

Slope, contributing area and topographic index were calculated for the reference (30 m aggregated high resolution), filled USGS and filled and elevation adjusted SIR-C DEMs using ARC/INFO algorithms as displayed in Figure 14 -Figure 21. The ARC/INFO algorithm calculates slope based on the method of steepest descent. The USGS and SIR-C DEMs exhibited larger ranges in slope than the reference DEM. The USGS DEM resulted in parameters that were closer to the reference product than the SIR-C DEM. The differences were apparent in spatial images of the topographic parameters. The valley network seen in the slope image is much more defined in the reference DEM than in the USGS product, and both are more clearly defined than the SIR-C DEM. The SIR-C image appears to be scattered,

resulting from abrupt changes in elevation. The drainage network defined by contributing area is more meandering than with the other DEMs. Differences in topographic index were mainly at the lower end of the distribution, which is not as hydrologically significant because the associated areas produce saturation excess relatively infrequently.

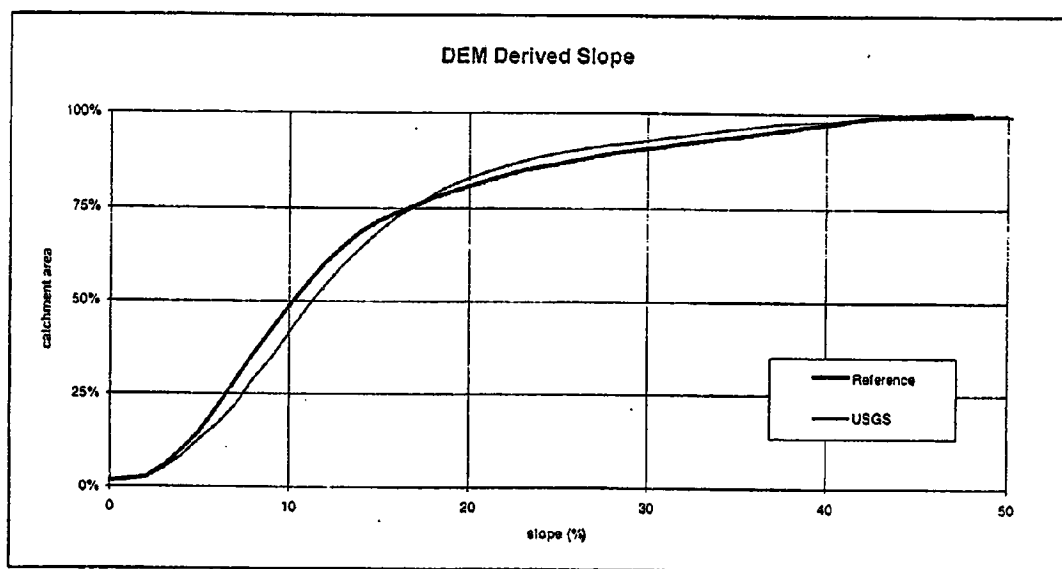


Figure 14. Cumulative distribution of slope

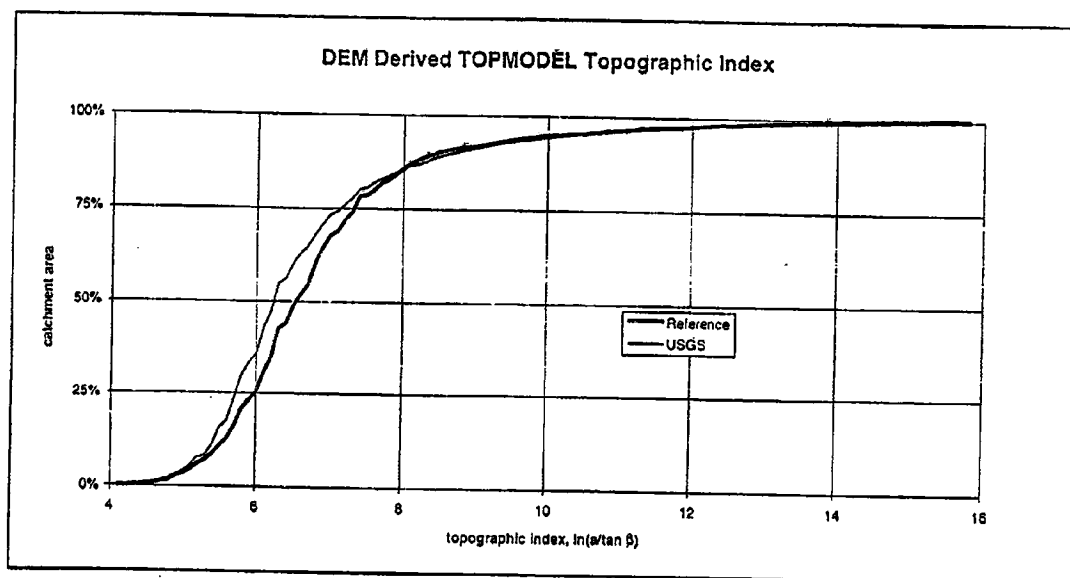


Figure 15. Cumulative distribution of topographic index

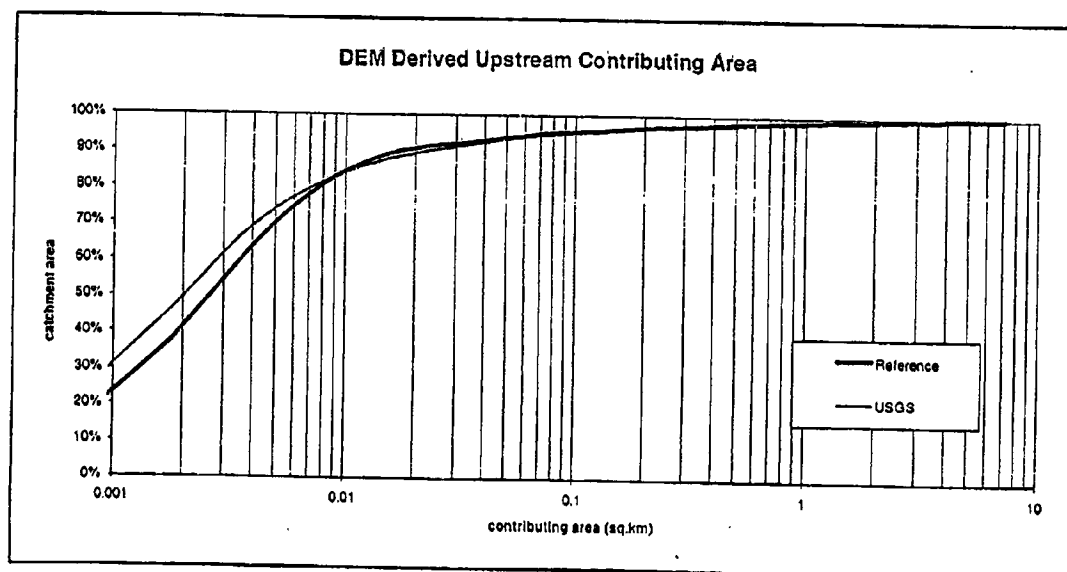
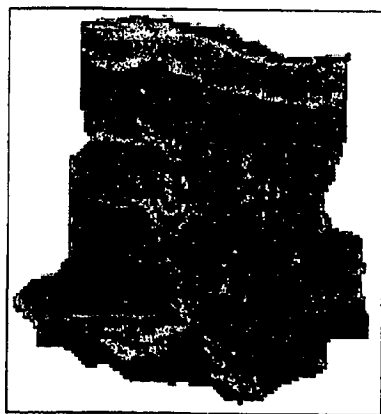


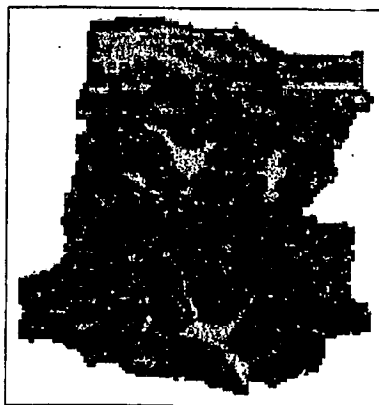
Figure 16. Cumulative distribution of contributing area



Reference Slope

maximum slope = 25.6 degrees

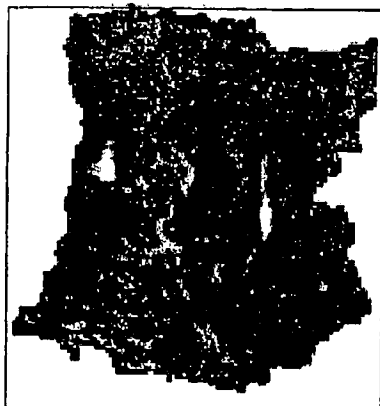
average slope = 7.7 degrees



USGS Slope

maximum slope = 38.2 degrees

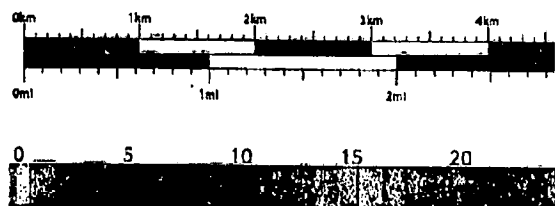
average slope = 7.5 degrees



SIR-C Slope

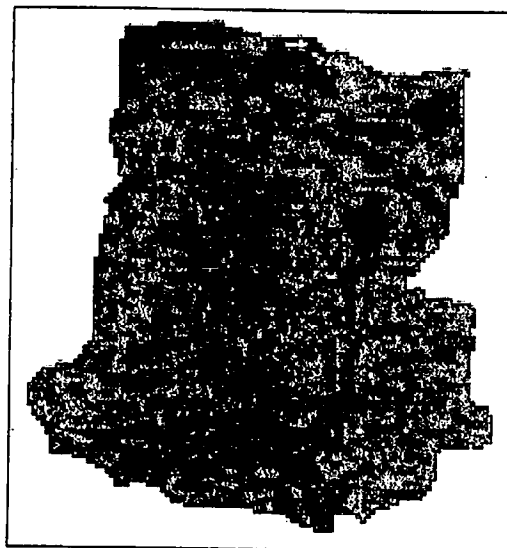
maximum slope = 39.2 degrees

average slope = 8.9 degrees



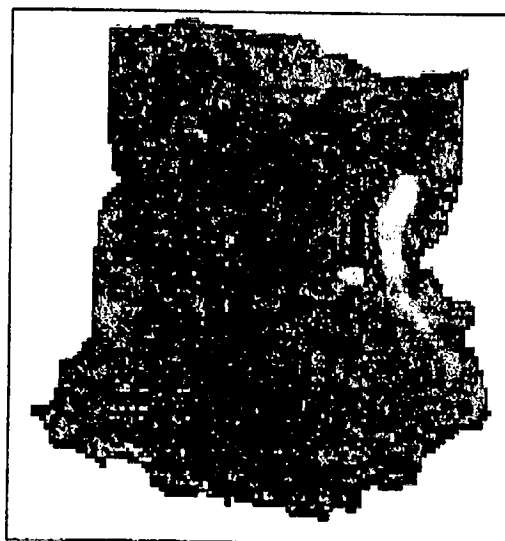
Slope (degrees)

Figure 17. Spatial distribution of slope



USGS slope - Reference slope

average difference = -0.3 deg
maximum difference = +22.1 deg
minimum difference = -16.1 deg



SIR-C slope - Reference slope

average difference = +0.9
maximum difference = +30.4 deg
minimum difference = -18.0 deg



Slope Difference (degrees)

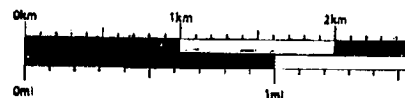
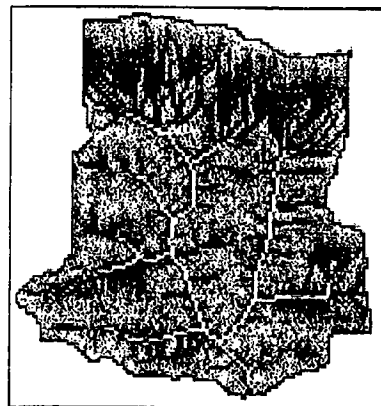
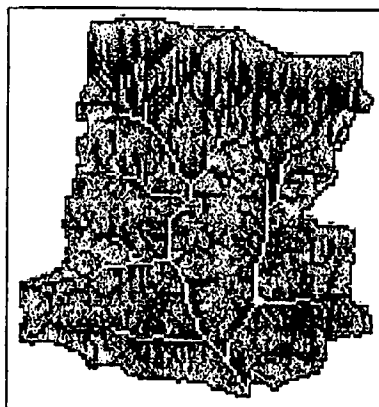


Figure 18. Spatial distribution of differences in slope



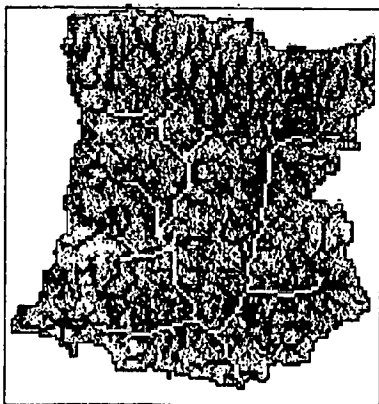
Reference Contributing Area

average area = 64.3 pixels
= 57,870 sq.m



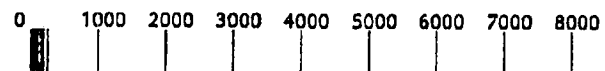
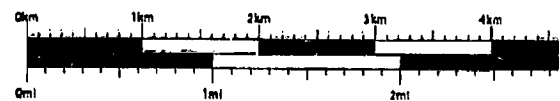
USGS Contributing Area

average area = 63.8 pixels
= 57,420 sq.m



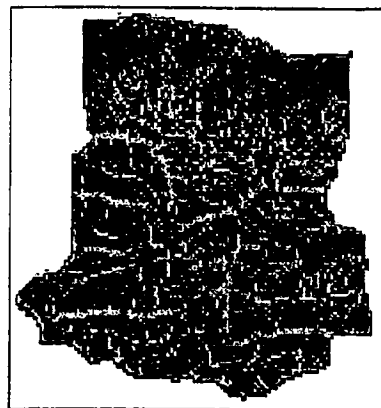
SIR-C Contributing Area

average area = 69.3 pixels
= 62,370 sq.m



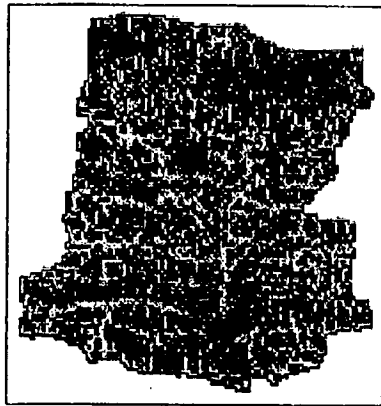
Upstream Area (# pixels @ 900 sq.m)

Figure 19. Spatial distribution of contributing area



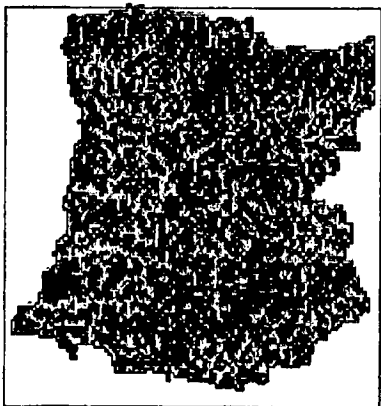
Reference Topographic Index

average topographic index = 6.888



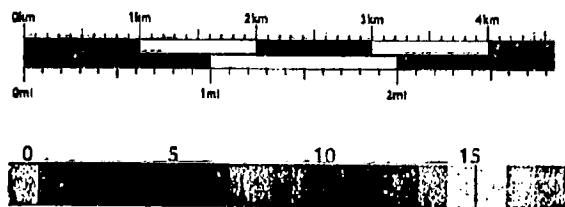
USGS Topographic Index

average topographic index = 6.081



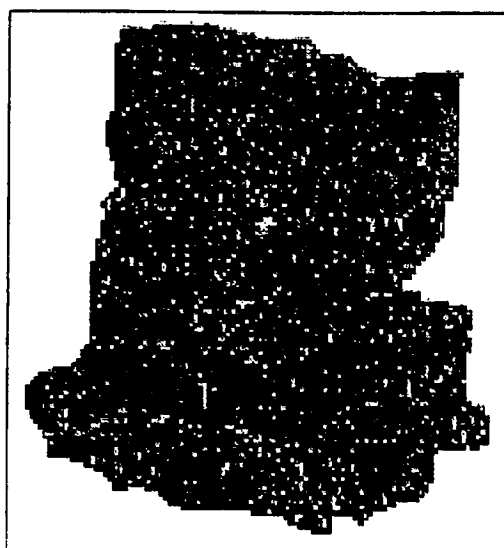
SIR-C Topographic Index

average topographic index = 5.483



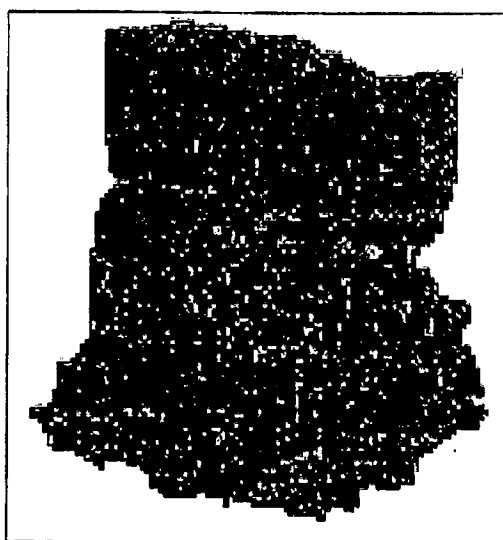
Topographic Index

Figure 20. Spatial distribution of topographic index



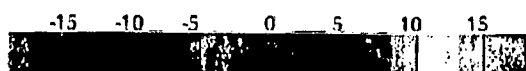
USGS Topographic Index -
Reference Topographic Index

average difference = -0.3



SIR-C Topographic Index -
Reference Topographic Index

average difference = +0.9



Topographic Index Difference



Figure 21. Spatial distribution of differences in topographic index

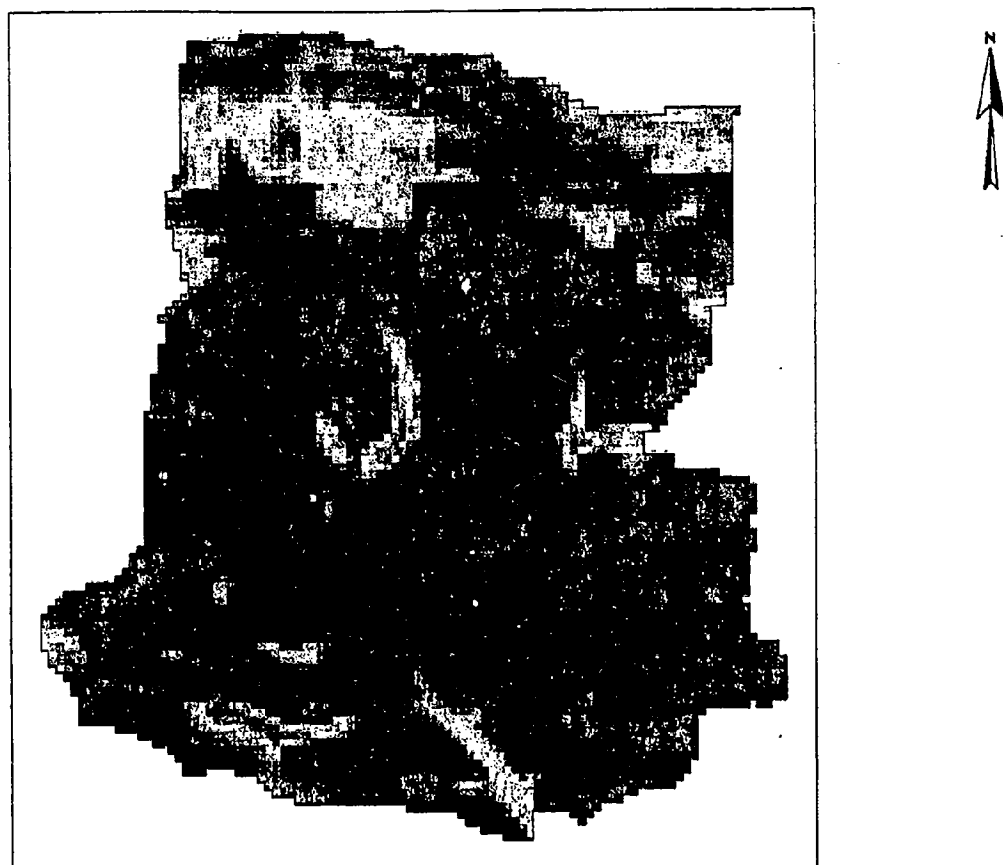
5. Error Structure of the USGS DEM

The USGS DEM displayed two types of discernible elevation differences from the reference DEM: a systematic grid-type error; and a pattern reminiscent of the basin topography (Figure 22). The possible source of these errors was examined and an error detection and correction algorithm was tested in an attempt to remove some of the errors.

5.1 Systematic errors

Abrupt changes in elevation differences are visible in the spatial difference images along N-S and E-W profiles. This grid-type error has previously been observed by Carter (1989). Carter examined standard USGS 7.5' DEM images and found linear error patterns with a cardinal orientation and artificial nature. These DEMs were derived by automated scanning of National High-Altitude Photography Program (NHAP) imagery using the Gestalt Photo Mapper II (GPM2). This is the same production process as described for the Valley View, PA standard USGS DEM (Section 2.1). Carter attributed errors to a lack of correlation between the edges of adjoining patches. Inspection of the NHAP images revealed areas of sun glint on the photos that would have prevented automatic correlation by the GPM2.

The DEMs studied by Carter were some of the earliest released by the USGS and predate the program of DEM correction that is now employed to remove obvious edge effects. Later DEMs were edge-smoothed to remove this problem. This smoothing process explains why the grid-type errors were not easily visible in the USGS DEM for Mahantango Creek: the smoothing process masks the edge effects by removing discontinuities but does not actually correct the correlation error by realigning the patch. The smoothed elevations are still in error and this error is visible when the DEM is evaluated, e.g. by comparison with a more accurate product.



Filled USGS DEM - Reference DEM

average difference = +5.53 m
maximum difference = +27.0 m
minimum difference = -23.0 m

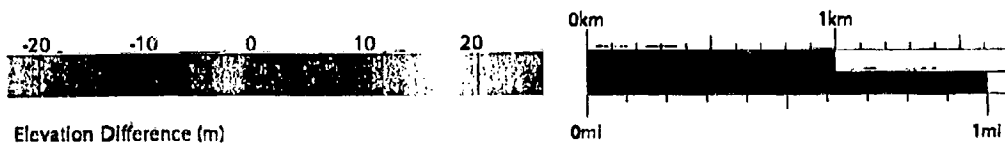


Figure 22. USGS Elevation Differences

5.2 Topographic errors

In addition to the edge error between patches, errors in USGS DEM elevations are also attributable to mismatches during the automatic correlation process of low-contrast images, relief-induced distortions between the images, and the presence of ambiguities due to identical objects or highly periodic textures on the terrain. These error sources can be related to topography. To examine this effect, the correlation between the USGS difference image and the basin topography was investigated by comparing the differences to topographical parameters. Elevations within two pixels of the edges of patches were excluded from this analysis in an attempt to remove the edge effect. No definitive mathematical relationship could be found between the differences and elevation or TOPMODEL topographic index although the data display distinct clusters (Figure 23 and Figure 24).

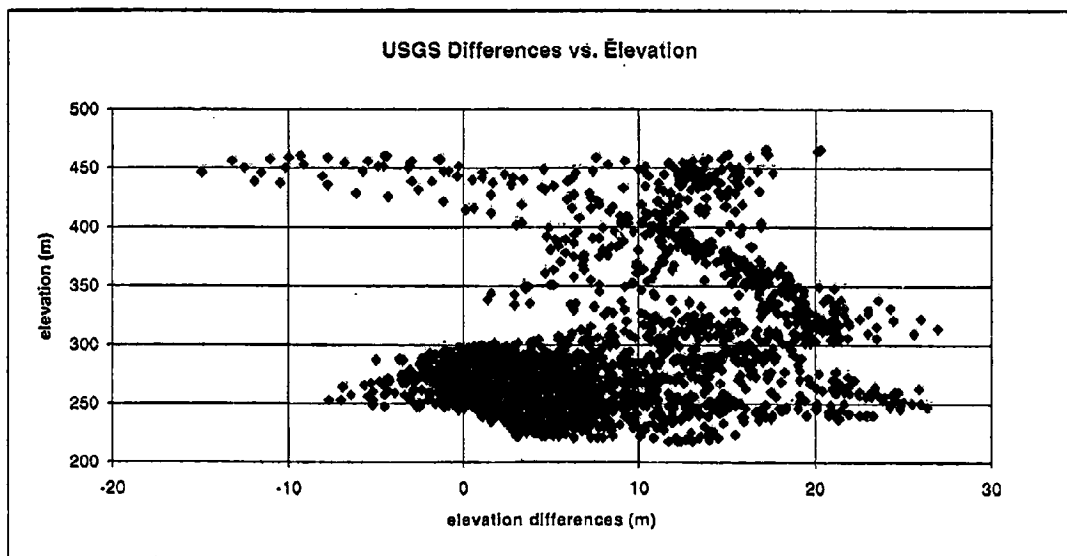


Figure 23. Elevation differences vs. elevation

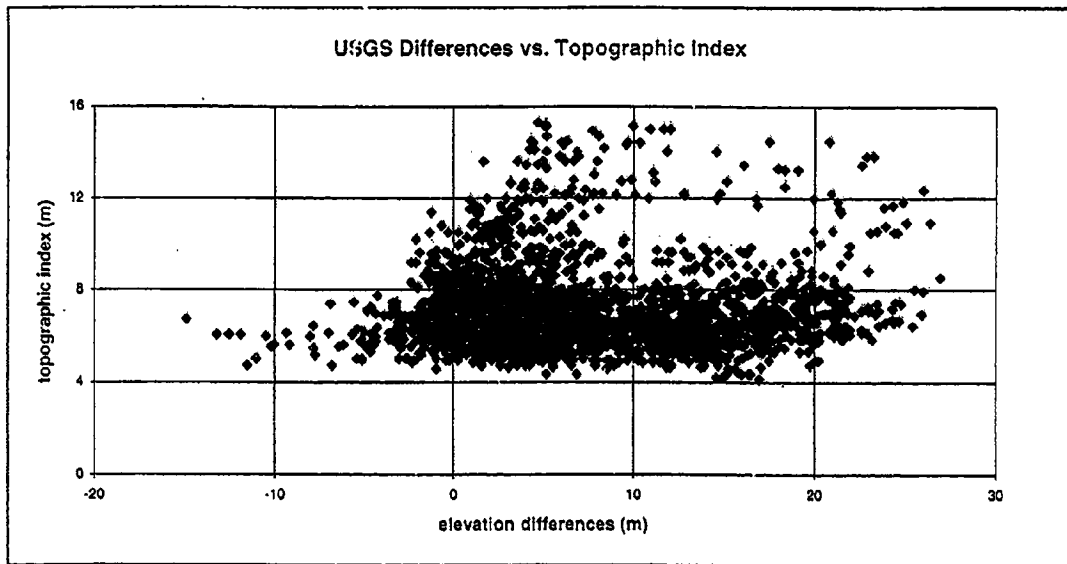


Figure 24. Elevation differences vs. TOPMODEL topographic index

Patches were categorized by terrain type, as either mountain ridge, stream channel or foot hills, in an attempt to separate the data clusters. Topographical parameters were considered separately for each terrain type. Average parameter values for each category are given in Table 6. Elevation differences are noticeably higher in mountainous areas and within the channel network where there are greater elevation variations. Plots of the differences for each category versus the topographic parameters gave different results for each terrain type but did not reveal any clear relationships (Figure 25, Figure 26 and Figure 27).

Table 6. Topographic parameters by terrain type

	<i>Mountainous Area</i>	<i>Channel network</i>	<i>Foot hills</i>
Average differences	9.66 m	4.88 m	3.95 m
Average elevation	338.46 m	260.34 m	270.41 m
Average contributing area	16,140 m ²	111,854 m ²	14,670 m ²
Average slope	13.56(x1)°	6.96°	7.11°
Average topographic index	6.62	7.12	6.56

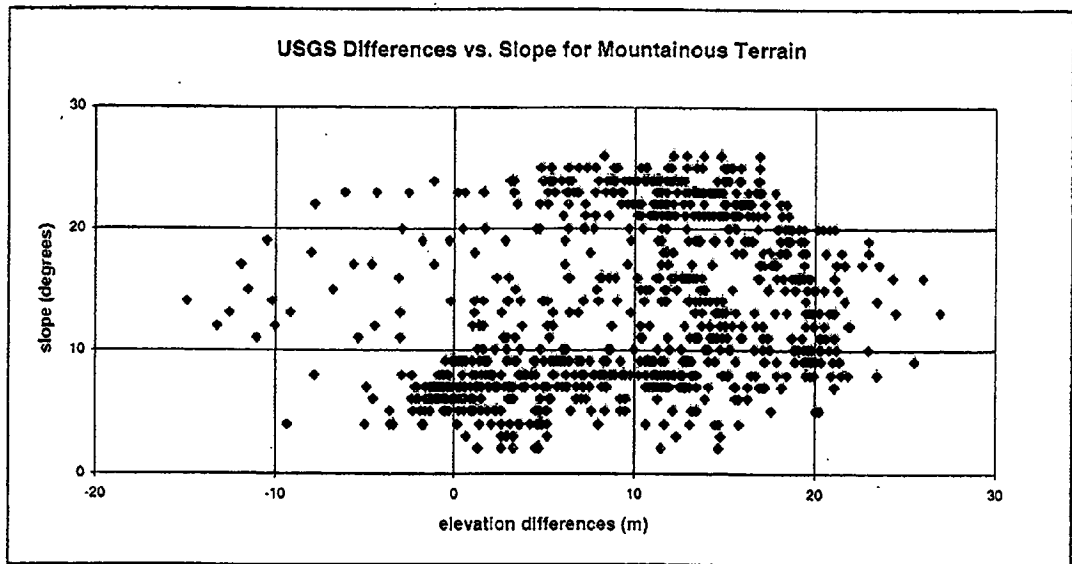


Figure 25. Elevation differences vs. slope for mountainous terrain

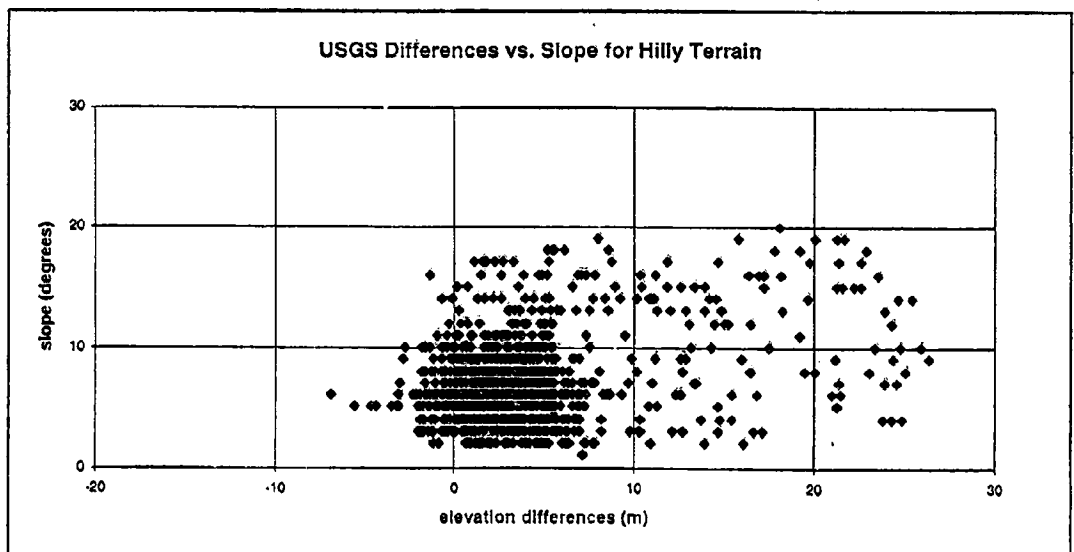


Figure 26. Elevation differences vs. slope for hilly terrain

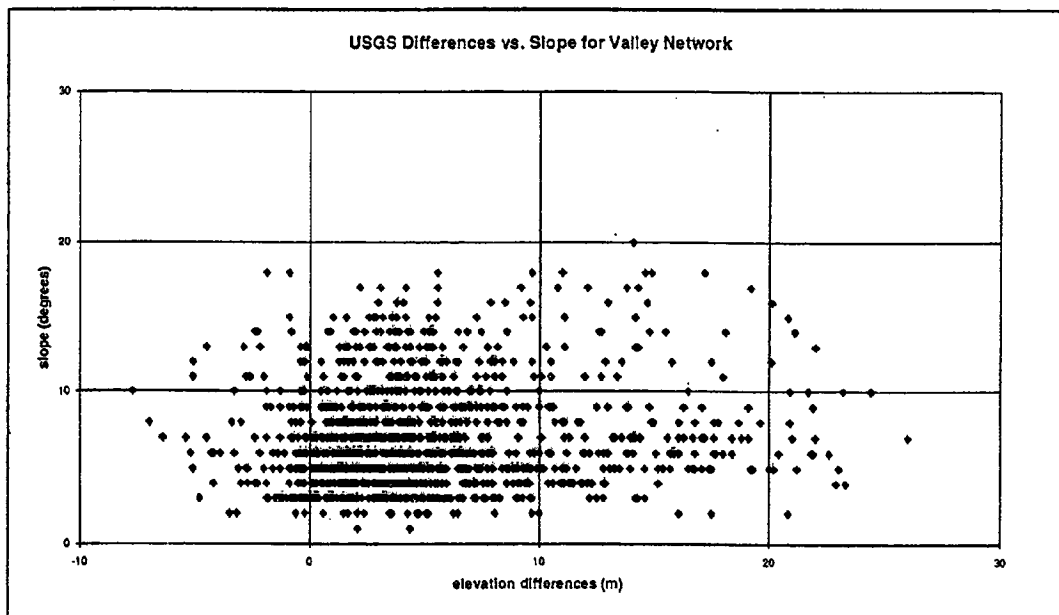


Figure 27. Elevation differences vs. slope for valley network

The mean and standard deviation of the differences varied greatly from patch to patch (Figure 28). The differences did display some correlation between topographic parameters and the elevation differences when examined separately. The nature of the relationship differed from patch to patch due to the different causes for local errors.

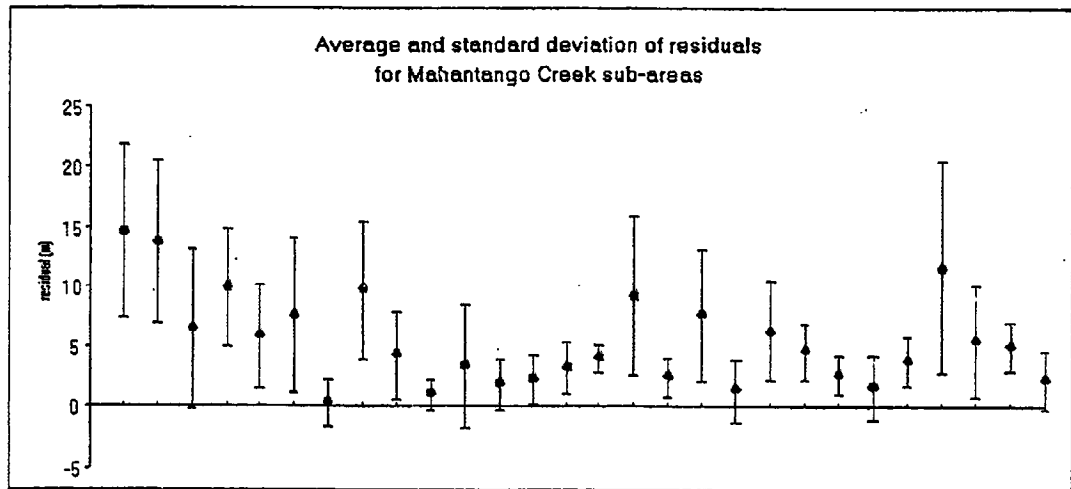


Figure 28. Mean and standard deviation of differences by patch

Along the ridges, differences were inversely related to elevations (Figure 29). This results from the proximity of lower elevation data to the top and bottom of the patch where the edge effect is most prominent. Elevation differences are much lower along the ridge, which is well-defined by the DEM.

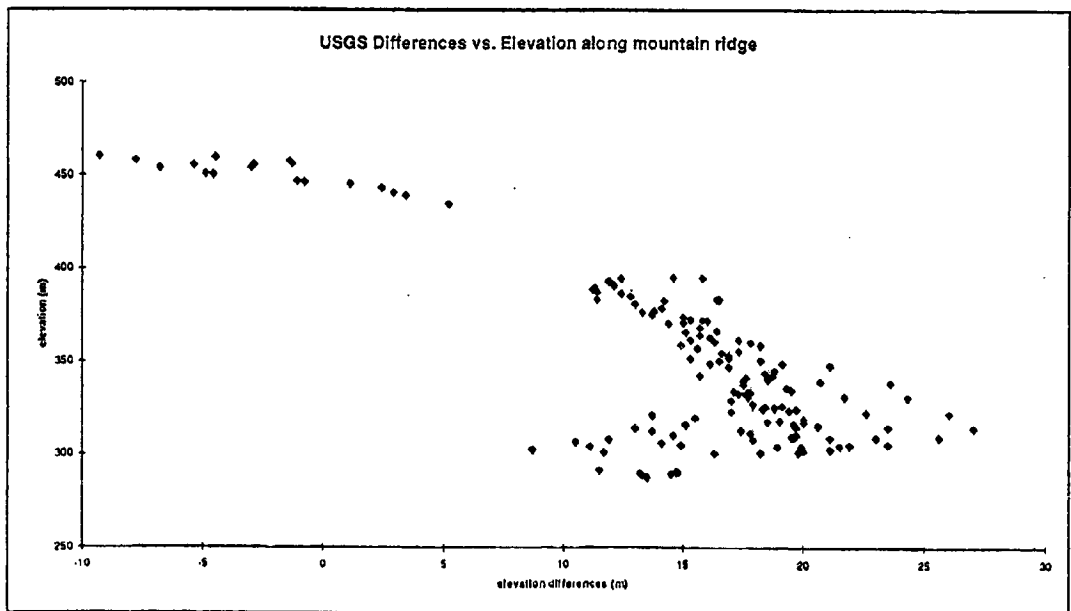


Figure 29. Residual vs. elevation in sub-area along mountain ridge

Differences in a patch in the lowlands in the south of the Mahantango Creek catchment were found to be inversely related to elevation and directly related to contributing area (Figure 30). This sub-area exhibited large differences in the area of the stream tributary where the USGS DEM failed to capture this topographic feature, which could be due to sun glint on the stream channel in the aerial photography.

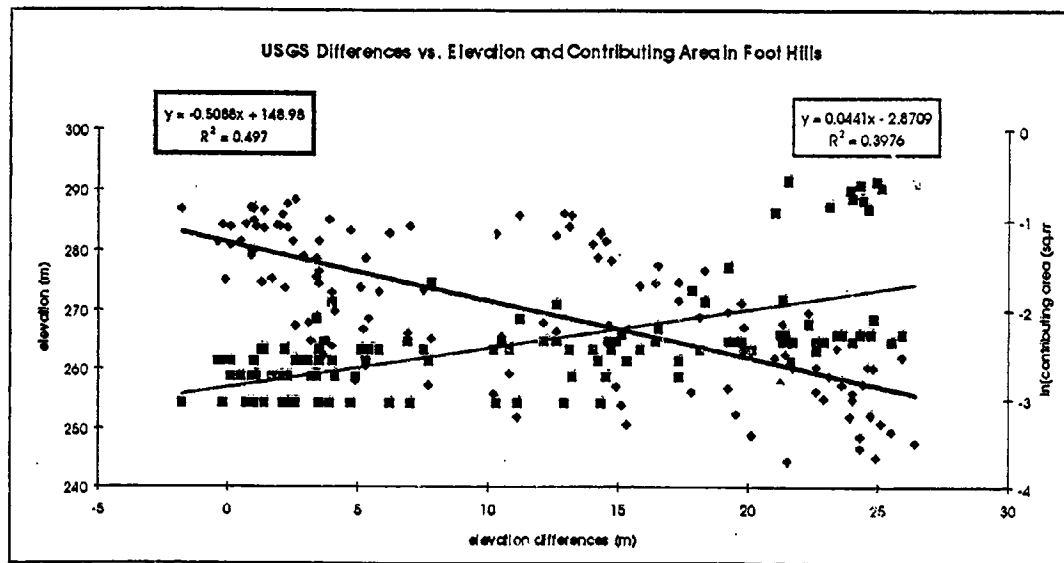


Figure 30. Elevation differences vs. elevation and contributing area in sub-area in foothills

5.3 Error detection and correction

Previous research on the detection and correction of local errors in digital elevation models has focused on the development of algorithms to check a model systematically for obvious errors. These methods are based on the assumption that topographic data are derived from a continuous surface which varies smoothly in elevation. Any data causing sharp discontinuities in the elevations or sudden changes in the surface slope are likely to be in error.

Hannah (1981) developed three sets of slope tests to detect error. The *slope constraining test* checks if the slope to any of the eight surrounding pixels exceeds a specified maximum. The *local neighbor slope test* checks the four pairs of slope crossing a point against a set maximum. The *distant neighbor slope consistency test* checks the pair of slopes approaching a point across each of the eight neighbors for consistency. A correctness indicator ranging from 0.0 (probably in error) to 1.0 (probably correct) is assigned to each elevation point based on the slope tests. Pixels with low correctness indicators are assumed to be erroneous and are replaced with the average of the elevations of the surrounding cells weighted by their respective correctness indicators. This correction process is repeated in an iterative fashion until changes are no longer significant.

Hannah's and similar tests are problematic in that they require the definition of threshold values for the slope or any other parameters used to detect errors. Felicísimo (1994) suggested a parametric test based on elevation differences that would not require threshold values. This method determines the difference between the elevation at a point and the elevation estimated for the point based on the neighboring cells. Bilinear interpolation of the elevations of the four cardinal neighbors is suggested to estimate the pixel elevation but more sophisticated techniques such as kriging can also be used. The mean and standard deviation of the differences are calculated and the Student *t* test is used to determine if each difference is within the population. Points outside of the population are assumed to be in error and are replaced with an interpolated elevation calculated from the neighboring cells.

Error detection methods which check a DEM for errors based solely on the DEM itself are used during the post-processing of DEMs to detect and correct errors that may have occurred in the correlation process. These tests are preferred for the detection of local errors over global techniques, such as curve fitting, which do not exclude points suspected to be in error from the final DEM.

Felicitimo's parametric test was used to determine if errors in the raw, unfilled USGS DEM could be identified and corrected. The Student t test was applied to every point as:

$$t_{i,j} = \frac{\delta_{i,j} - \delta}{s_{\delta}} \quad (3)$$

where $\delta_{i,j}$ is the difference between the elevation at a point and the elevation estimated from an average of the four cardinal neighbors. δ and s_{δ} are the mean and standard deviation of all the differences, respectively.

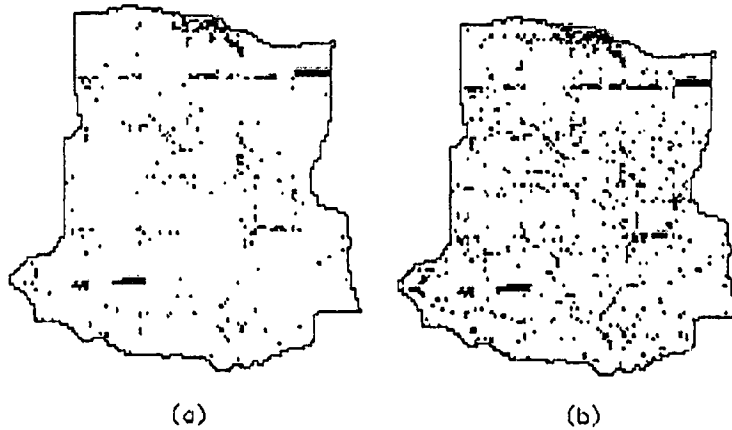


Figure 31. Rejected data points at (a) 90% and (b) 80% confidence level

The rejected points at 90% ($t_{i,j} > 1.645$) and 80% ($t_{i,j} > 1.282$) confidence levels are shown in Figure 31. 4.2% of the elevations were rejected at the 90% confidence level and 8.8% were rejected at the 80% level. The spatial distribution of the t statistic identifies some of the error patterns seen in the differences but the test was not able to completely identify either the systematic production errors or the

errors related to basin topography. Other elevation estimators, averaging the four diagonal neighbors or a weighted average of all eight neighbors, were tested for their ability to detect the errors and were found to perform in a similar fashion.

Rejected points were replaced with a bi-linear interpolation of the elevations of the four cardinal neighbors. This correction algorithm was not effective at resolving differences between the USGS DEM and the reference product. The corrected spatial difference image displays the same error patterns and results in a higher mean and standard deviation of errors (Table 7).

Table 7. Elevation differences between USGS and reference DEMs

<i>USGS DEM</i>	<i>Minimum Difference</i>	<i>Maximum Difference</i>	<i>Average Difference</i>	<i>Standard Deviation</i>
Original	-24.3 m	27.0 m	7.45 m	11.30 m
Corrected	-19.3 m	34.3 m	8.57 m	11.42 m

It was not surprising that the edge effects could not be completely eliminated by the parametric error detection. This method relies on comparisons between the pixel elevation and an estimate of the neighboring grid cell elevation. Smoothed data which have been averaged over a group of cells will not be found to be in error. To correct the edge effect properly, the patches should be repositioned based on a more accurate correlation with neighbors. This repositioning may require lifting, lowering or tilting of the patch with respect to surrounding areas.

6. Hydrological Model of the WE-38 Watershed

The Distributed Soil-Hydrology-Vegetation Model (DHSVM) was used to simulate streamflows and hydrologic fluxes on a 3-hour timestep for a continuous four year period starting October 1, 1983. Simulations were run using each of the three DEMs.

6.1 Input data

DHSVM requires specification of vegetation and soils information, as well as meteorological forcing data and the initial hydrological state variables for each pixel. In addition, a number of model parameters must be specified.

6.1.1 Vegetation types

Multi-polarization C-band (5.8cm wave length) and L-band (23.5cm wavelength) SIR-C images were taken over the Mahantango Creek watershed from space shuttle Endeavor on April 14, 1994. Niko Verhoerst (previously at Princeton University) derived land cover classifications from these data. A classifier program, based on work by Pierce et al (1994), was used to designate the vegetation class of each pixel (12.9 m azimuth by 13.3 m range) as urban, tall vegetation, short vegetation, or bare surfaces (Figure 32). The tall vegetation class defines areas of deciduous hardwood forest, short vegetation refers to cropland and bare surface is pasture land. Overstory and understory properties were defined for each vegetation class as reported in Appendix B. The areas of each terrain type differ from a previous descriptions of the basin land coverage by Pionke and Kunishi (1992) who reported larger cropland area and less forested areas (Table 8).

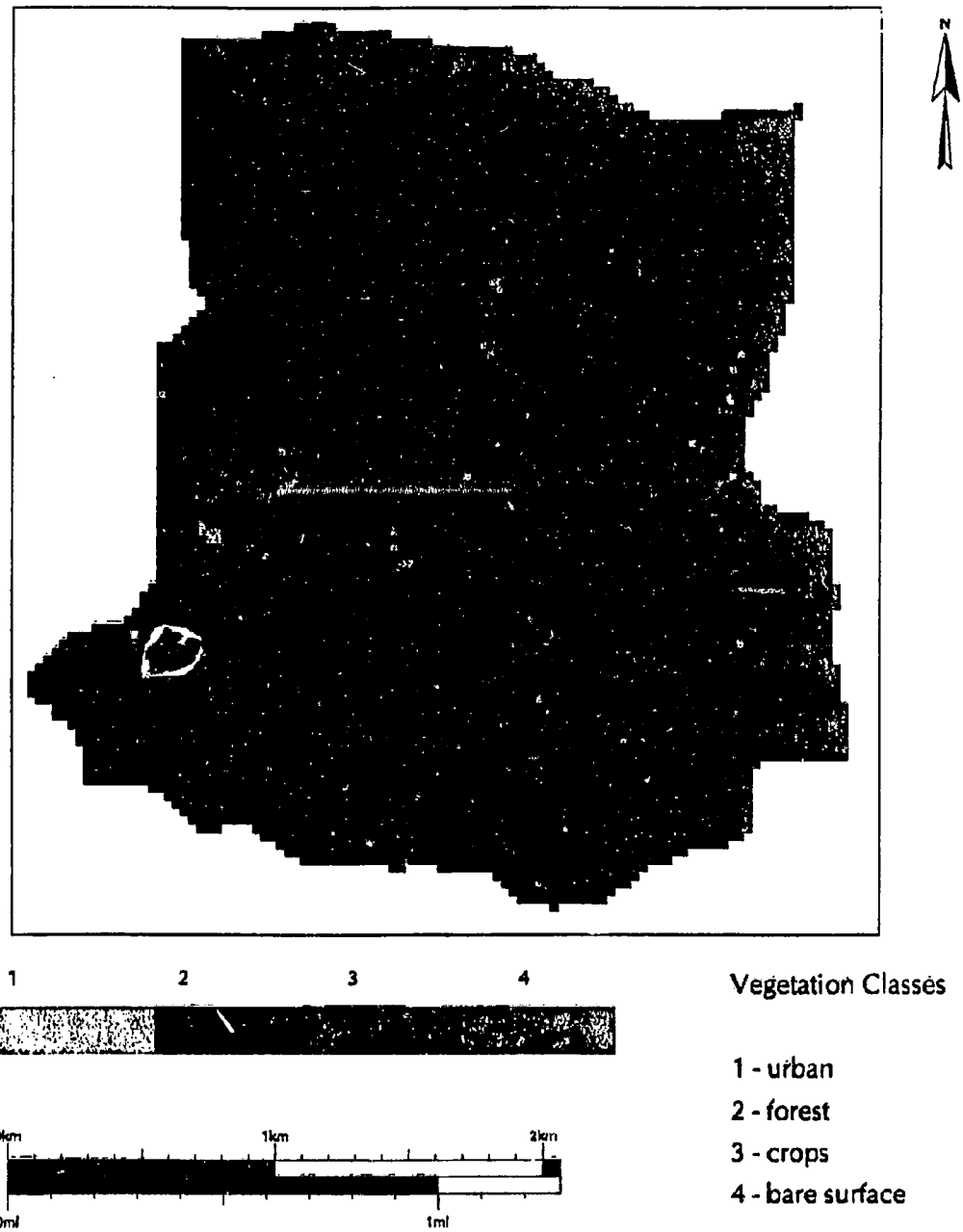


Figure 32. Mahantango Basin vegetation types

Table 8. Vegetation classifications

<i>Vegetation class</i>	<i>Description</i>	<i>SIR-C defined area⁵</i>		<i>Literature Description⁶</i>
1	urban	0.03 km ²	0.4%	-
2	tall vegetation	4.01 km ²	55.6%	35%
3	short vegetation	3.11 km ²	43.1%	57%
4	bare surfaces	0.06 km ²	0.8%	8%

6.1.2 Soil types

Distributed soil classifications for the Mahantango Creek research watershed were developed by Peter Troch (Ghent University) based on the USDA Soil Conservation Service (SCS) county soil surveys (Figure 33). 15 soil types were identified over the basin (Table 9). The majority of the soils are silt loam. Soil parameters were provided by the SCS for each soil type as reported in Appendix B.

⁵ Determined by Niko Verhoerst using a classifications based on interferometric SAR images

⁶ Pioke and Kunishi, 1992.

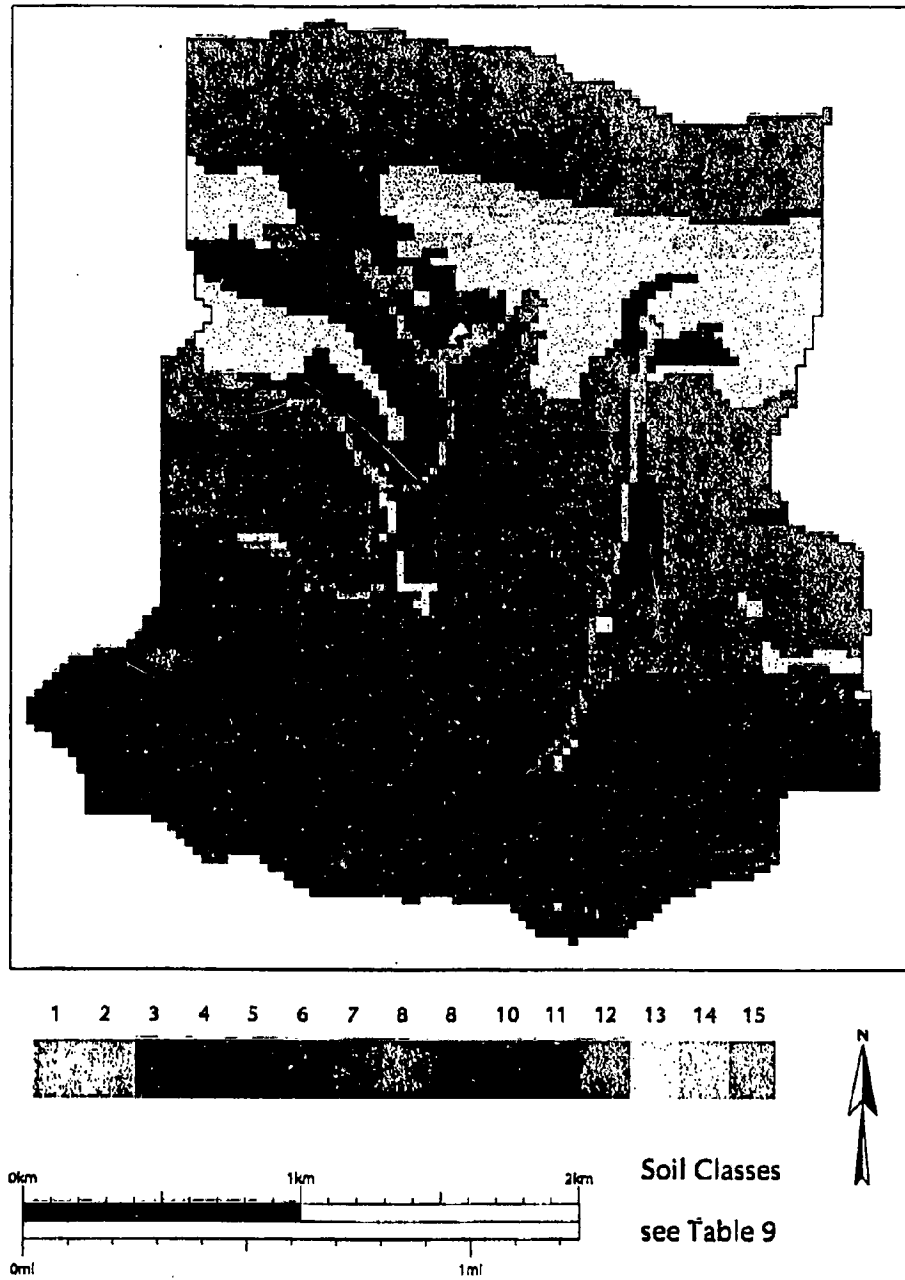


Figure 33. Mahantango Basin soil types

Table 9. Soil classifications

<i>USDA Soil Classification</i>	<i>Soil name</i>	<i>Description</i>	<i>Area (km²)</i>
1	Albright	silt loam	0.20
2	Alvira	silt loam	0.10
3	Basher	silt loam	0.10
4	Berkes	silt loam	0.64
5	Calvin	silt loam	0.21
6	Conyngham	silt loam	0.06
7	Dekalb	sandy loam	0.97
8	Harleton	silt loam	1.19
9	Klinesville	silt loam	0.69
10	Laidig	gravel loam	0.14
11	Leck Kill	silt loam	1.47
12	Meckesville	loam	0.84
13	Meckesville	stony loam	0.19
14	Shelmadine	silt loam	0.05
15	Weickert	silt loam	0.36

6.1.3 Meteorological data

Daily records of maximum and minimum temperature, relative humidity and wind speed were taken at the MD-38 meteorological station located at the USDA-ARS Pasture Systems & Watershed Management Research Laboratory in the Mahantango Creek watershed. These data were used to construct 3-hourly records of cloud coverage, relative humidity, wind speed, air temperature, and incoming long wave radiation.

Cloud cover was calculated from estimates of clear sky and net short wave radiation based on the daily maximum and minimum temperature and the elevation of the temperature station using equations from Bras (1990):

$$f = \sqrt{\frac{1}{0.65}} * \sqrt{1 - \frac{I'_s}{I_c}} \quad (4)$$

$$I_c = 0.6 + 2.95 \times 10^{-5} * z \quad (5)$$

$$I'_s = I_c * \left\{ 1 - \exp \left[b * (T_{\max} - T_{\min})^{2.4} \right] \right\} \quad (6)$$

where f is the cloudiness factor, I'_s is the net short wave radiation, I_c is clear sky radiation, z is elevation (244.0 m), T_{\max} is daily maximum temperature (°C) and T_{\min} is the daily minimum temperature (°C).

Resulting cloudiness factors were normalized from zero to one with zero representing clear sky conditions and one representing completely overcast conditions. Cloud coverage, relative humidity and wind speed are assumed to be constant throughout the day.

Air temperature was calculated as the sum of a fraction of the minimum temperature of the previous day, the current minimum and maximum temperature and the minimum temperature on the following day (Table 10) based on the method of Anderson (1968).

Table 10. Estimation of air temperature

<i>Time</i>	<i>% Previous Day T_{max}</i>	<i>% Current T_{min}</i>	<i>% Current T_{max}</i>	<i>% Next Day T_{min}</i>
24:00 - 3:00	19%	81%	-	-
3:00 - 6:00	5%	95%	-	-
6:00 - 9:00	2%	68%	30%	-
9:00 - 12:00	-	40%	60%	-
12:00 - 15:00	-	21.3%	76.3%	2.4%
15:00 - 18:00	-	2.5%	92.5%	5%
18:00 - 21:00	-	1.25%	62.75%	36%
21:00 - 24:00	-	-	33%	67%

Dew point temperature was calculated from the air temperature and the relative humidity using an approximation given by Maidment et al (1993) as:

$$T_d = \frac{237.3}{\left[\frac{17.27}{\ln\left(\frac{e_s}{0.6108}\right)} - 1 \right]} \quad (7)$$

$$e_s = \frac{RH}{100} * e \quad (8)$$

$$e = 0.6108 * \exp\left(\frac{17.27 * T}{237.3 + T}\right) \quad (9)$$

where T_d is the dew point temperature($^{\circ}\text{C}$), T is the air temperature ($^{\circ}\text{C}$), RH is the percent relative humidity, e_s is the saturation vapor pressure and e is the actual vapor pressure at the prevailing temperature.

Incoming long wave radiation was calculated from air and dew point temperature and cloud cover based on equations from Maidment et al (1993) as:

$$L_i = (1 - f) * \epsilon' * \sigma * (T + 273.3)^4 + f * \sigma * (T_d + 273.3)^4 \quad (10)$$

$$\epsilon' = 0.740 + 0.0049 * e_s \quad (11)$$

where L_i is incoming long wave radiation ($\text{MJ}/\text{m}^2/\text{day}$), T_d is the dew point temperature ($^{\circ}\text{C}$), T is the air temperature ($^{\circ}\text{C}$), e_s is the saturation vapor pressure, ϵ' is the net emissivity between the atmosphere and the ground and σ is the Stefan-Boltzmann constant ($4.903 \times 10^{-9} \text{ MJ}/\text{m}^2/\text{sec}/^{\circ}\text{K}^4$).

Precipitation records were extracted from the ARS database for two long-term precipitation gages, (see Figure 3). The raw data were recorded in breakpoint format with readings taken each time the cumulative precipitation exceeded 0.1 inch. These data were aggregated to 3-hourly records for the period of interest.

Clear sky solar radiation was estimated for each pixel using the model of Dubayah et al (1990) as coded in Image Processing Workbench (IPW) (Frew, 1990; Longley et al, 1992). The model computes clear sky radiation which is partitioned into direct and diffuse beam components, accounting for the date, time of day, pixel location, slope, aspect and the effects of shading or reflection of radiation from surrounding terrain. Diffuse and direct beam radiation is calculated monthly for each pixel based on the distribution of the solar radiation at the solar midpoint of each month and then discretized into ten equiprobable classes.

6.1.4 Basin parameters

Those parameters which were assumed not to vary spatially are given in Table 11.

Table 11. Basin constant parameters

<i>Parameter</i>	<i>Value</i>
K_{sat} saturated horizontal hydraulic conductivity	0.06 m/hr
K_{sat} exponential decay coefficient	30 m
snow roughness length	0.015
wind measurement height	27.0 m
vapor pressure deficit causing stomatal closure	4.0 mb
visible light fraction of total short wave radiation	0.5
meteorological station elevation (md38, me37)	244.0, 284.0 m
temperature lapse rate	0.007 °C/m
dew point lapse rate	0.0055 °C/m
maximum temperature for precipitation as snow	3.3 °C
minimum temperature for precipitation as rain	0 °C
precipitation location adjustment factor	1.37
maximum snow pack surface layer (water equivalent)	0.125 m
depth of soil below the rooting zones	1.0 m

6.1.5 Initial soil moisture

To produce realistic initial conditions, a one-year "warmup" run was made starting with constant initial soil moisture on October 1, 1983. Since DHSVM is a continuous simulation model, the effect of the initial conditions are expected to be insignificant after the first water year (October - September) once the

basin has become saturated during the spring high runoff period. Spatial predictions of depth to saturation and soil moisture in the rooting zones for October 1, 1984 were then used as the initial conditions for the four year simulation which started October 1, 1983, with each DEM. Ideally the warmup year would not have been reused however this procedure was thought to be justified given the relatively short four year period for which coincident meteorological data were available.

6.2 Model testing

As DHSVM is a physically-based model, the surface characteristics data represent physical descriptions of the watershed and should not require calibration. However, some input data are not known with great accuracy (e.g. leaf area index, albedo) and other data are constructed from a coarser timestep (e.g. humidity, wind speed) or from other estimated parameters (i.e. solar radiation, cloud cover). Some of the parameters listed in Table 11 are assumed not to vary spatially for convenience alone (e.g. saturated hydraulic conductivity) and soils and vegetation parameters that must of necessity be assumed constant also introduce errors in model predictions.

Predicted streamflows for the Mahantango WE-38 watershed as defined by the reference DEM were compared to observed records to ensure that DHSVM was able to model the hydrologic processes adequately. As DHSVM is being used for a sensitivity analysis to determine the effects of difference in the DEMs, exact model predictions were not necessary, however, it was required that the model be representative of the hydrologic behavior of the watershed. Results for the 1983/84 water year are reported in Figure 34 and the remaining years are reproduced in Appendix D. Other hydrologic fluxes were also examined to confirm that they were appropriate for the basin climatology and hydrology.

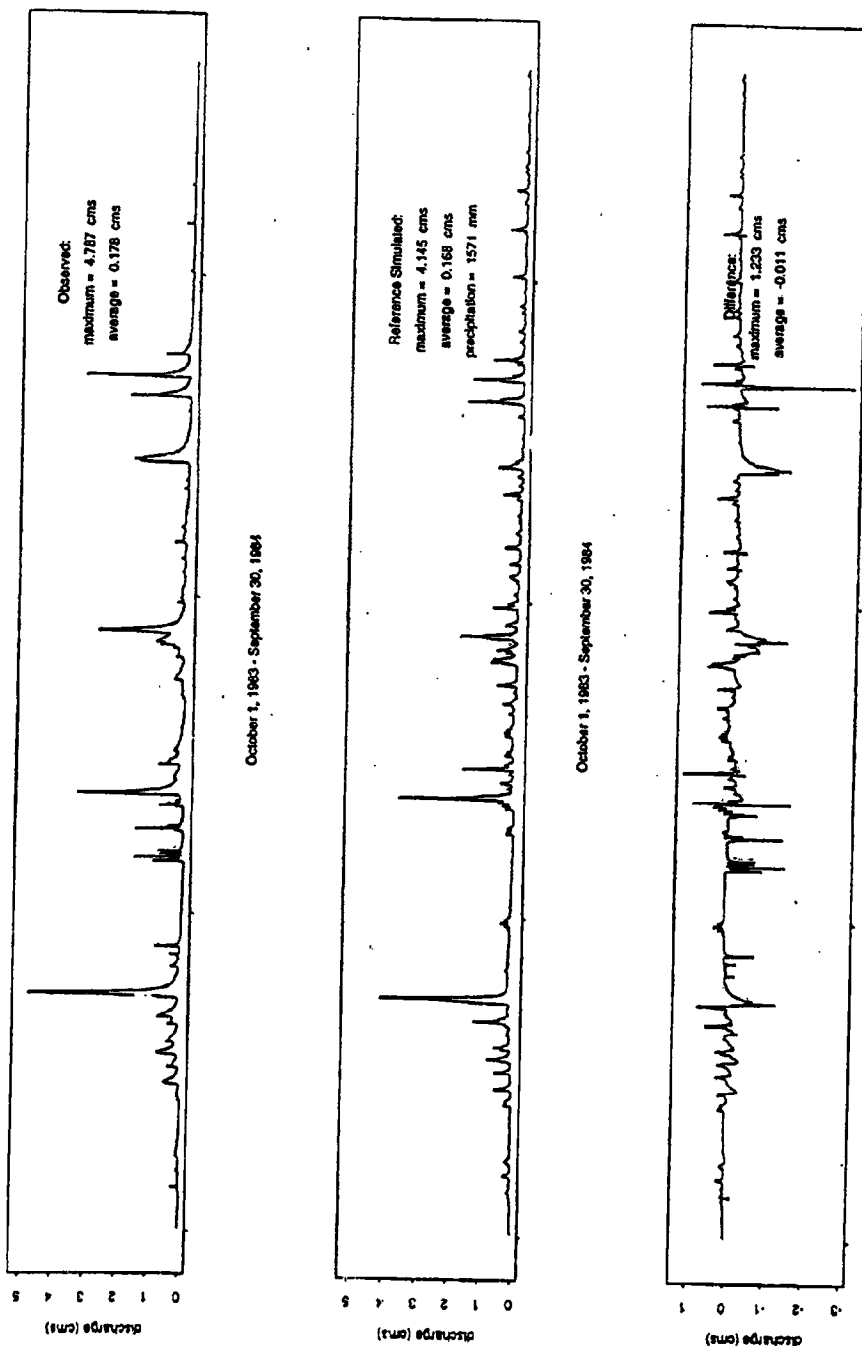


Figure 34. Calibration differences, 1983/84 water year

7. Hydrologic Results

DHSVM computes hydrologic fluxes at each grid cell continuously. This information can be output as a basin-average or single-pixel time series for any time period within the record or as a spatial basin image for a single timestep. For this analysis, spatial distribution of precipitation, depth to saturation and runoff production were examined during both high and low flow periods. Time series predictions of streamflow based on each DEM were compared with observed records at the WE-38 weir.

7.1 Precipitation

Precipitation at each pixel is an input variable for the model. Precipitation observations were available at two meteorological stations on the basin (see Figure 3). Precipitation at each gage was lapsed to the elevation of each pixel using the adjustment shown in Figure 35. As both meteorological stations are located in the lower part of the watershed, observed precipitation was also scaled by a basin-constant factor to avoid a downward bias of runoff predictions.

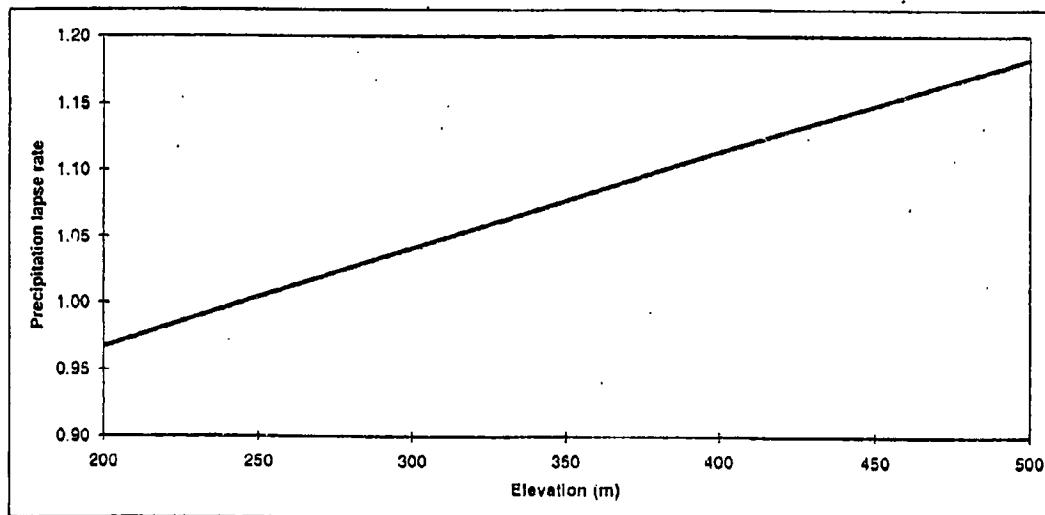


Figure 35. Precipitation adjustment factor

The digital elevation data directly influence the precipitation input when it is lapsed to the pixel elevation for each grid cell. However, because the cumulative elevation distribution functions are similar for each of the DEMs (see Figure 10), the basin mean monthly values are not significantly different (Table 12).

Table 12. Average monthly precipitation (mm)

	<i>Reference DEM</i>	<i>USGS DEM</i>	<i>SIR-C DEM</i>
October	56.6	56.9	56.9
November	123.6	124.3	124.3
December	86.3	86.8	86.8
January	44.4	44.6	44.6
February	71.7	72.0	72.1
March	73.5	73.9	73.9
April	90.1	90.6	90.6
May	106.6	107.1	107.2
June	144.4	145.1	145.2
July	125.0	125.6	125.7
August	101.8	102.3	102.4
September	119.3	119.9	119.9

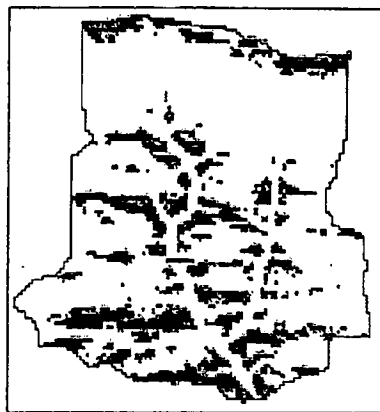
7.2 Soil moisture and runoff production

Spatial images of the instantaneous depth to saturation and runoff production on December 14, 1983 are reproduced in Figure 36 and Figure 37. Depth from the surface to the water table during the high flow and low flow events of each year (Table 13), and runoff production during the high flow events are reproduced in Appendix C. DHSVM uses the DEM explicitly and does not require inputs of slope.

contributing area and topographic index. However, the spatial distributions of these topographic parameters were found to be similar to those of depth to saturation and runoff production. This is not surprising as the topographic index, although not used directly in DHSVM, is an indicator of the runoff producing tendency of a cell based on its slope and upstream contributing area. The valley network is more pronounced in spatial predictions of depth to saturation and runoff production based on the reference DEM. The lower resolution DEMs resulted in scattered spatial images of soil moisture and low runoff production. This suggests that model predictions based on the reference DEM are more representative of the physical processes occurring within the basin.

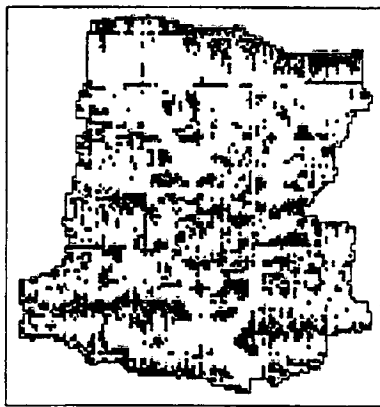
Table 13. Events selected for spatial images of soil moisture

<i>Year</i>	<i>High flow event</i>	<i>Low flow event</i>
1983-1984	December 14, 1983, 15:00	July 26, 1984, 24:00
1984-1985	February 13, 1985, 15:00	August 30, 1985, 24:00
1985-1986	March 15, 1986, 24:00	January 15 1986, 24:00
1986-1987	September 14, 1987, 24:00	August 5, 1987, 24:00



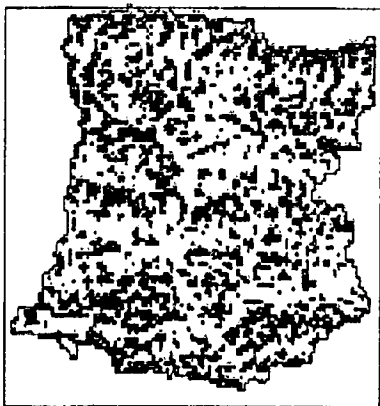
Reference Depth to Saturation

average depth = 134 mm
maximum depth = 514 mm



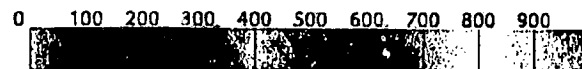
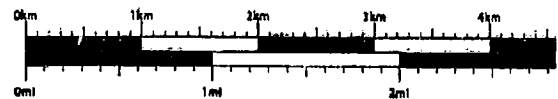
USGS Depth to Saturation

average depth = 175 mm
maximum depth = 674 mm



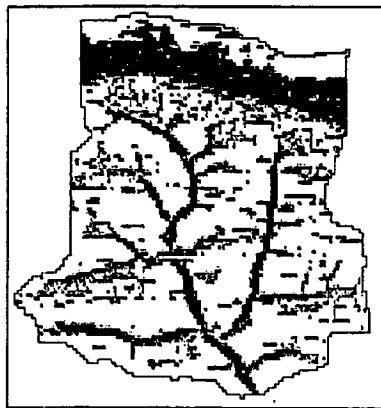
SIR-C Depth to Saturation

average depth = 259 mm
maximum depth = 895 mm



Depth to Saturation (mm) on Dec 14, 1983, 3 pm

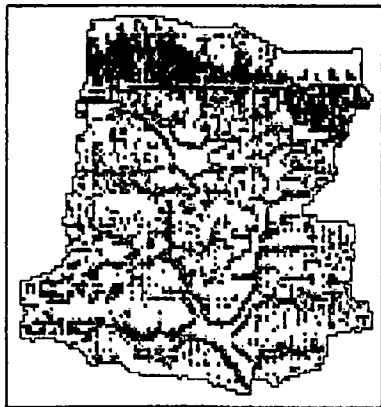
Figure 36. Spatial distribution of depth to saturation, December 14, 1983



Reference Runoff Production

average runoff depth = 1.1 mm

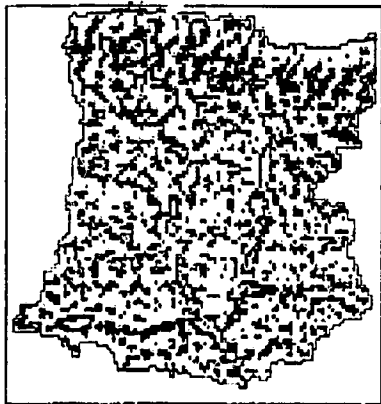
maximum runoff depth = 6.0 mm



USGS Runoff Production

average runoff depth = 1.3 mm

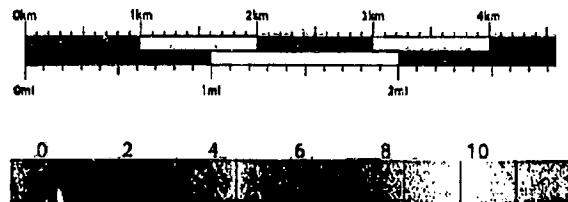
maximum runoff depth = 12.0 mm



SIR-C Runoff Production

average runoff depth = 1.7 mm

maximum runoff depth = 13.0 mm



Runoff Production (mm) on Dec 14, 1983, 3 pm

Figure 37. Spatial distribution of runoff production, December 14, 1983

7.3 Streamflow

Simulated streamflow volumes were found to vary between the three DEMs in a consistent fashion. Mean runoff volumes were lowest when predicted by the reference DEM. The USGS and SIR-C DEMs predicted average annual flows that were 0.3% and 7.0% larger, respectively (Table 14 and Table 15). The distinct increase in predictions by the SIR-C DEM is attributable to the 3.6% larger basin area and a higher basin average elevation. The basin average elevation is affected by the datum shift selected for the SIR-C DEM which was chosen to adjust the DEM to a consistent basin outlet elevation.

Table 14. Annual summary of flows (cms)

<i>Year</i>	<i>Observed</i>	<i>Reference DEM</i>	<i>USGS DEM</i>	<i>SIR-C DEM</i>
1983-1984	0.1802	0.1689	0.1692	0.1790
1984-1985	0.0747	0.0794	0.0781	0.0836
1985-1986	0.1557	0.1508	0.1534	0.1649
1986-1986	0.1150	0.1189	0.1188	0.1266
Average	0.1314	0.1295	0.1299	0.1386

Time series plots were examined for individual events series (Figure 38 - Figure 41) for each water year (Appendix D). These hydrographs showed that the reference simulation had a higher peak and lower recession than flows simulated with the USGS and SIR-C DEMs. These differences could be expected from the differences in the topographic index. The USGS and SIR-C DEMs had higher lower topographic indices which indicates a lower runoff production capacity. The SIR-C DEM is less smooth than the reference DEM with abrupt changes in slope and a meandering channel that could not transport water to saturated pixels as efficiently as the reference DEM. Surface flow was reduced by the lack of defined channel network. The USGS DEM had a smaller average contributing area which resulted in shorter travel times to the outlet and lower peak flows.

Table 15. Monthly summary of flows during four simulation years (cms)

	<i>Observed</i>	<i>Reference DEM</i>	<i>USGS DEM</i>	<i>SIR-C DEM</i>
October	0.0318	0.0672	0.0615	0.0649
November	0.1556	0.1352	0.1324	0.1339
December	0.2073	0.2204	0.2300	0.2596
January	0.0726	0.1243	0.1271	0.1293
February	0.2388	0.1923	0.1928	0.1950
March	0.1803	0.1791	0.1819	0.1955
April	0.2267	0.1685	0.1708	0.1865
May	0.1246	0.0909	0.0890	0.0926
June	0.1025	0.0958	0.0949	0.1037
July	0.0595	0.0787	0.0775	0.0798
August	0.1032	0.0912	0.0911	0.1015
September	0.0739	0.1101	0.1098	0.1204
Average	0.1314	0.1295	0.1299	0.1386

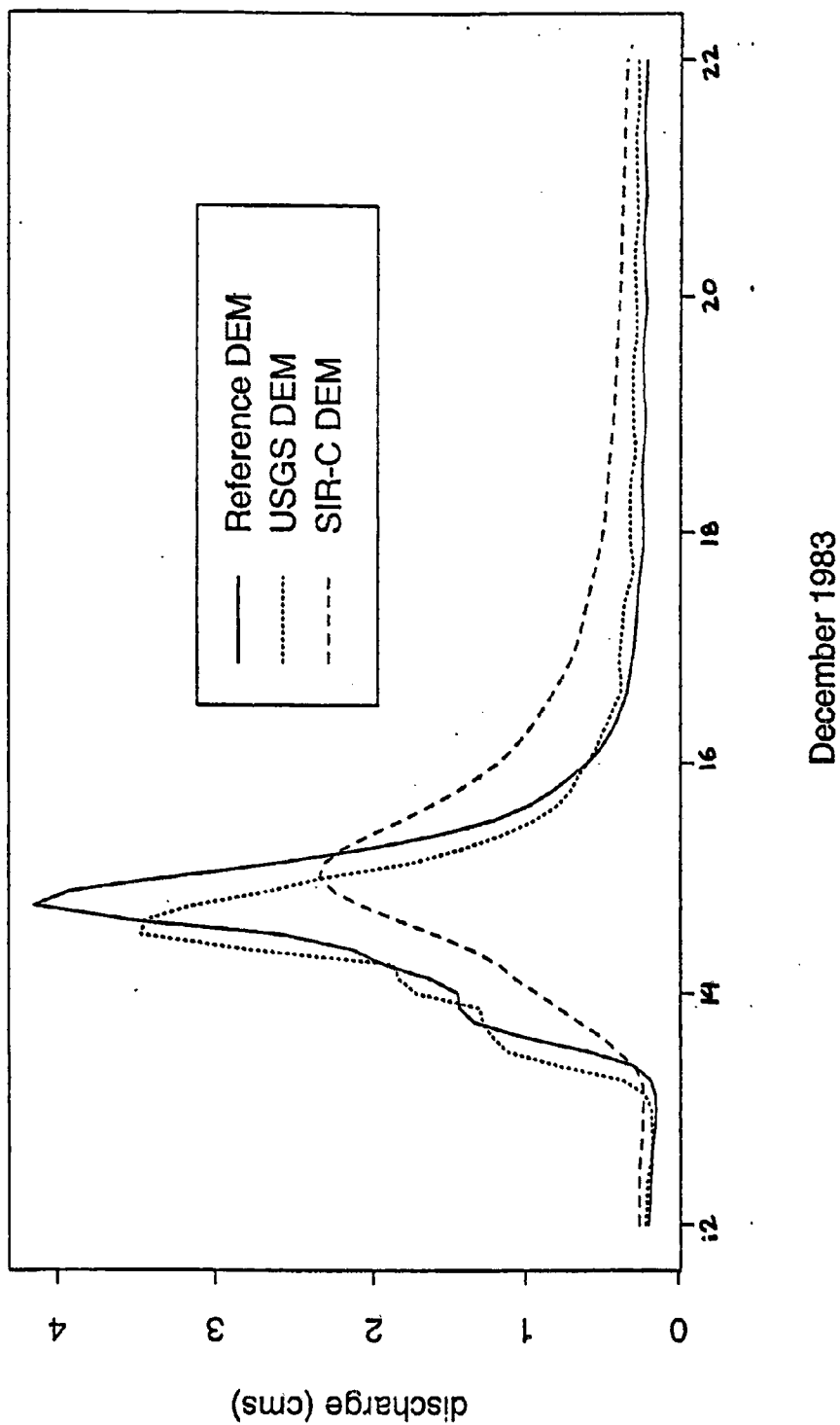


Figure 38. Simulated high flow event, December 14, 1983

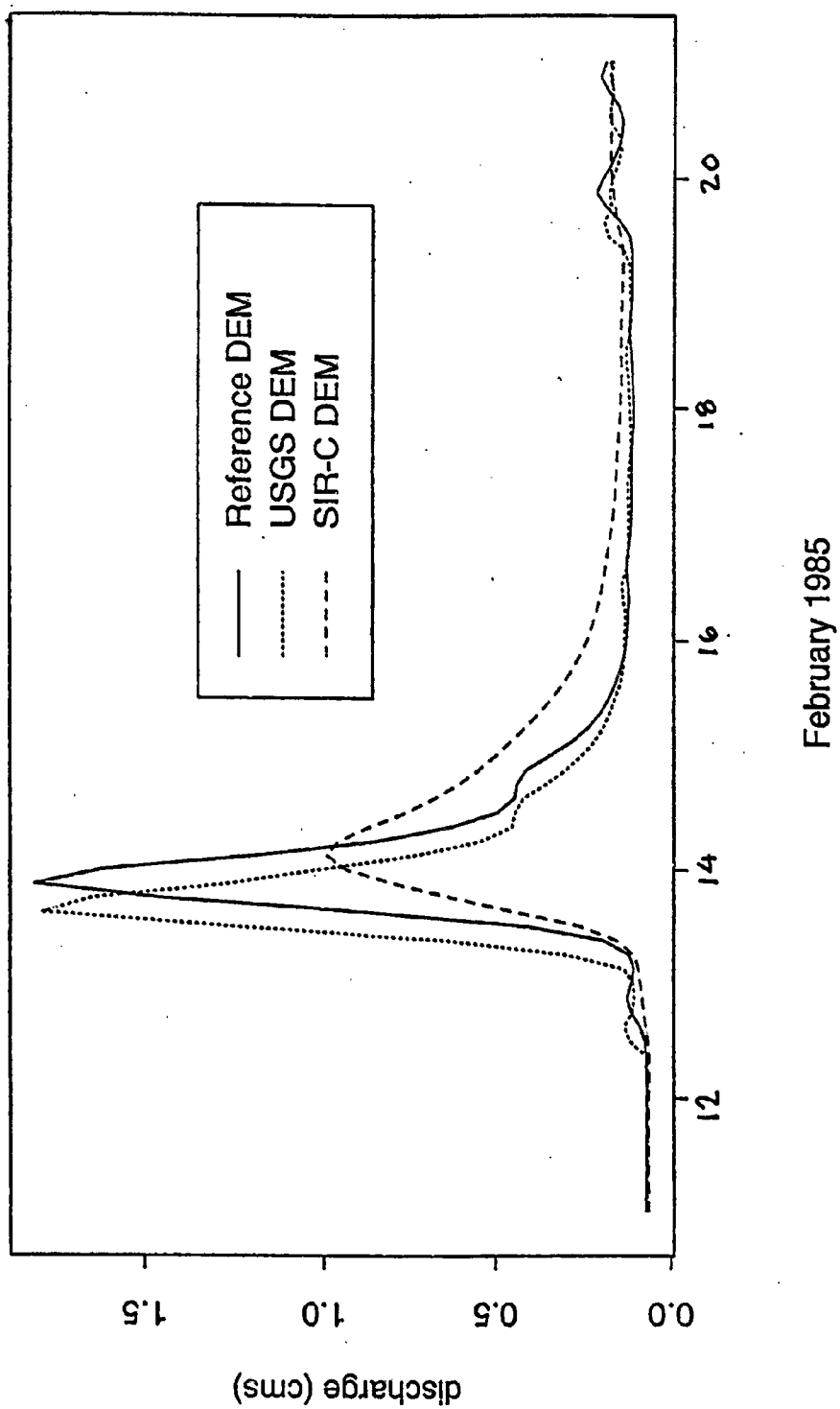


Figure 39. Simulated high flow event, February 13, 1985

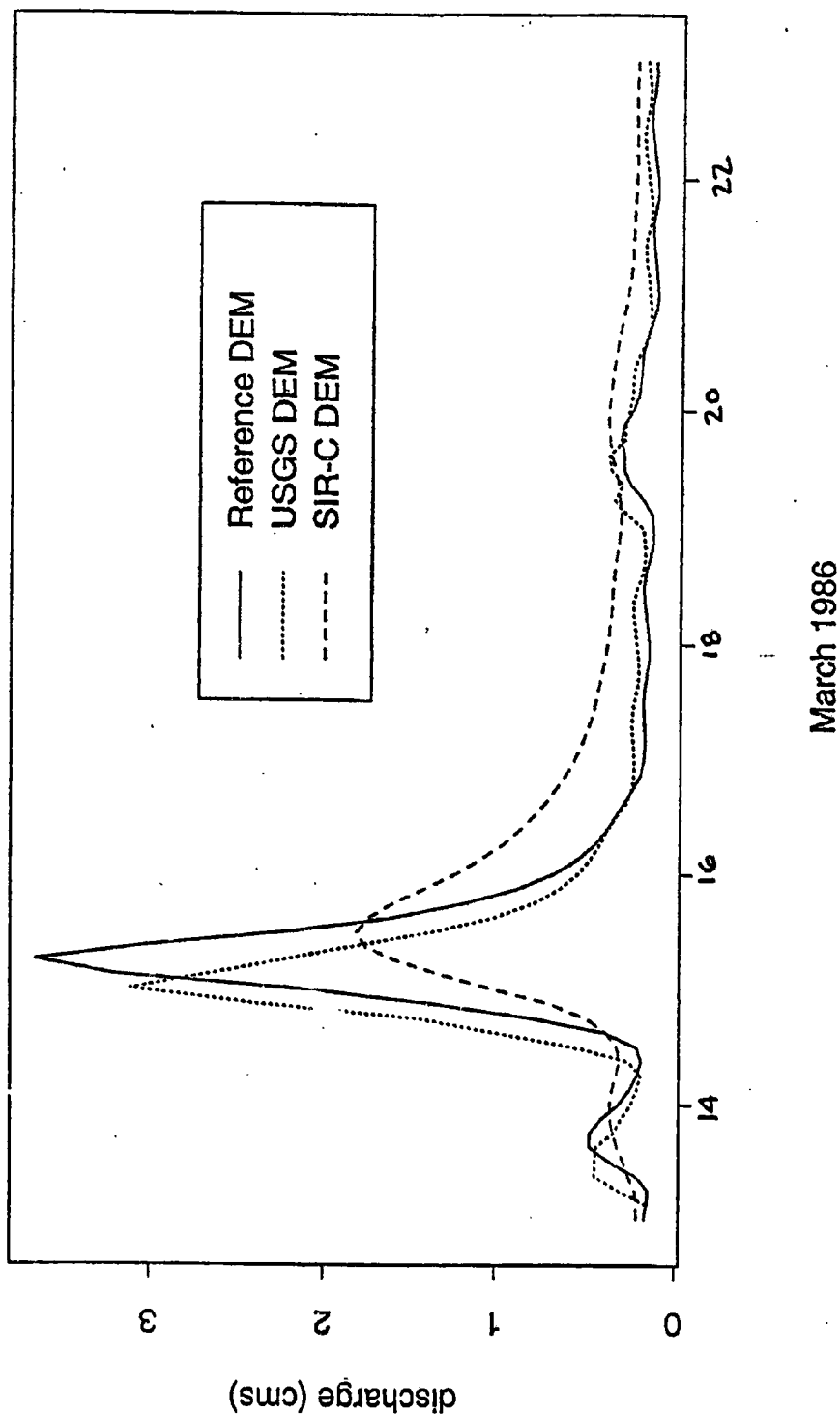


Figure 40. Simulated high flow event, March 15, 1986

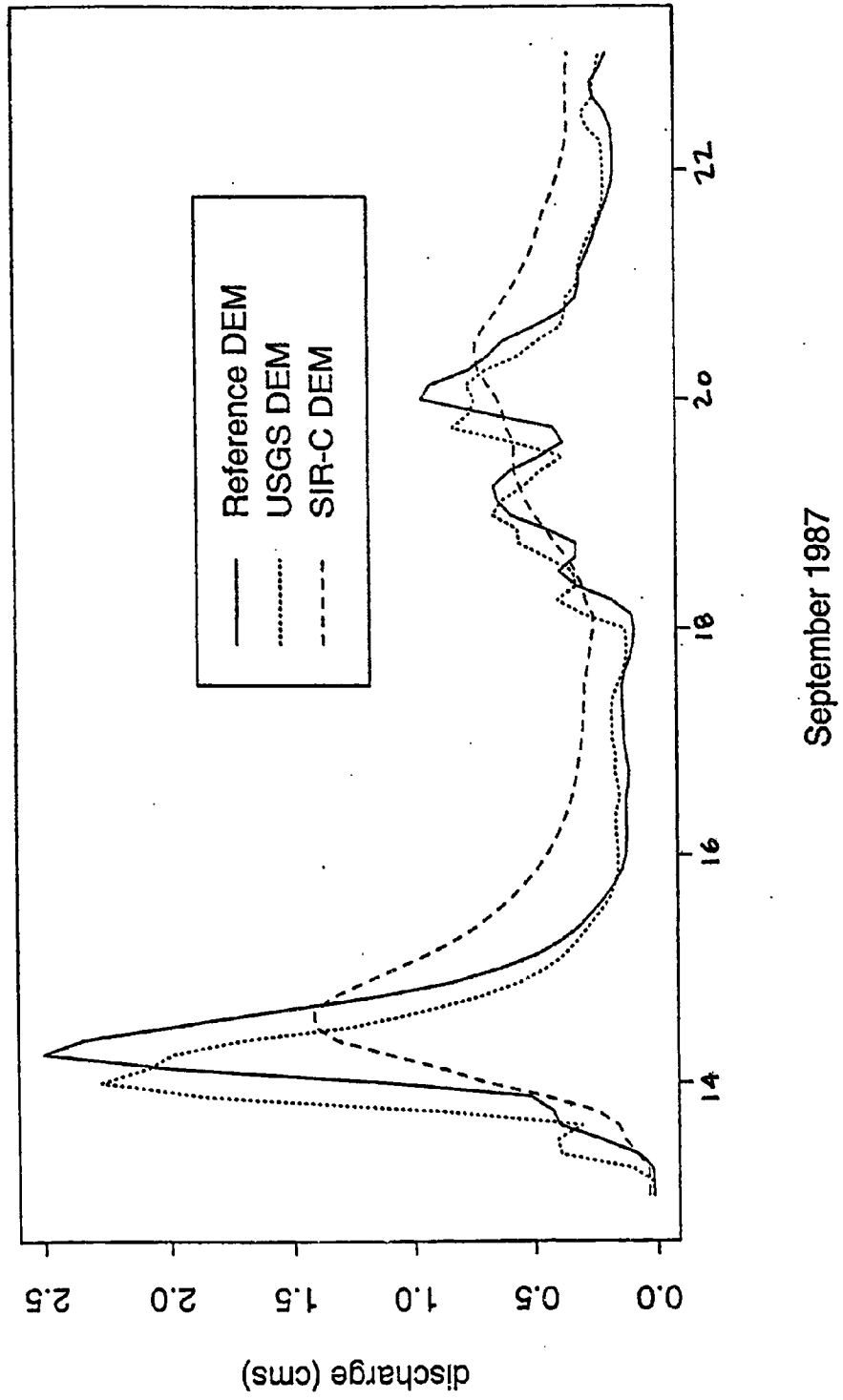


Figure 41. Simulated high flow event, September 14, 1987

8. Conclusions and Recommendations for Further Research

8.1 Summary

A high resolution 5 m DEM was derived from low altitude aerial photography of the USDS-ARS experimental watershed in the Mahantango basin. This DEM was aggregated to a 30 m resolution using code provided by Barros and Bindlish (1996) based on their modified fractal interpolation scheme and used as a reference DEM. The reference DEM was compared to the standard 30 m USGS 7.5' DEM and a third DEM produced by NASA/JPL using interferometric processing of SIR-C images.

ARC/INFO algorithms were used to delineate the watershed boundaries using each DEM and to calculate basin area and outlet elevation. Elevation differences between the reference product and the USGS and SIR-C DEMs were calculated and analyzed spatially and statistically. Nine check points on the watershed were compared to the elevations reported in each DEM. The basin topographic attributes of slope, contributing area and topographic index were calculated from each DEM and compared spatially and statistically.

Differences between the USGS and reference DEMs were studied to determine the source of the errors and any correlation between the elevation differences and the topographic parameters. Correction algorithms were applied in an attempt to correct the systemic errors observed in the USGS DEM.

DHSVM was calibrated with the reference product for the Mahantango Basin. Flow and moisture fluxes were predicted using each of the 30 m DEMs for a four year period beginning October 1, 1983. Spatial images of the instantaneous depth to saturation and runoff production were examined and compared to the spatial distribution of parameters derived directly from the DEMs. Predicted runoff volumes were compared on an annual and monthly basis and individual events were analyzed to determine the dependence of the shape and timing of the runoff hydrograph to the DEM used for the hydrologic simulation.

8.2 Results and Discussion

Significant elevation differences were found between the reference DEM derived from high resolution aerial photography and the DEMs derived by standard USGS methods and SIR-C interferometry.

The standard USGS DEM displayed two distinct errors: a systemic grid-type error due to the edge effect introduced during the automated scanning of the NHAP photographs in small patches; and a error pattern which reflected the basin topography attributable to a lack of correlation between the two photographs. Neither error could be eliminated using Felicimo's parametric test because the errors were not strictly local but instead were consistent over a patch or topographic area. Linear relationships were found between the USGS elevation differences and topographic parameters for some individual patches a clear error structure could not be determined for the entire watershed or by different terrain area because of the wide range of error sources.

The watershed boundaries delineated from the USGS DEM were more irregular than those determined with the reference product although the basin drainage areas agreed to 0.04%. The USGS DEM contained more sink pixels than the reference DEM (110 and 5 sink pixels, respectively) and was higher on average (+7.5 m) and at the outlet (+22.1 m). The valley network was visible on the USGS DEM and in spatial images of topographic parameters although it was less distinct than in the reference product. This is due in part to error in the USGS DEM within the valley bottoms and the edge matching error which resulted in a misalignment of the drainage network.

The SIR-C DEM differed visibly from the reference, particularly in areas of high slopes. The spatial image has a scattered appearance with rough boundaries. The watershed area delineated from the SIR-C DEM was 3.6% larger than the reference area, 4.5% of its pixels did not drain and required filling, and the elevations were consistently lower (-50.5 m at the outlet). The difference in elevation was attributed to a datum error and the DEM was uniformly elevated by 50.5 m. The resulting average elevation was 8.1 meters higher than the reference product, indicating that the error was not consistent

across the basin. Comparison of the spatial distribution of topographic parameters confirmed that reference DEM better represented the physical attributes of the watershed. The valleys defined by the SIR-C DEM were more meandering with more higher order tributaries.

DHSVM was used to simulate runoff production in the Mahantango Basin for the four year period beginning October 1, 1983, using each of the DEMs. Differences in predictions were always more significant between the SIR-C and reference DEMs than between the USGS and reference DEMs, which is consistent with the direct comparisons of these products. The USGS standard and SIR-C DEMs predicted average annual flows that were 0.3% and 7.0% larger than those predicted by the reference DEM, respectively. The small increase using the USGS DEM for predictions is attributable to the higher basin average elevation while the higher predictions using the SIR-C DEM are caused by the higher basin average elevation combined with a larger drainage area.

Differences in the DHSVM spatial predictions of depth to saturation and runoff production reflected the differences seen in the spatial images of topographic parameters. This is because the runoff producing tendency of a cell is related to slope and contributing area, although these parameters are not used explicitly in DHSVM which works directly from the elevation.

The shape and timing of simulated runoff hydrographs for individual events also differed for the three DEMs. The USGS DEM predicted lower peaks that rose sooner which reflects the small contributing area seen in the USGS DEM. The SIR-C DEM resulted in the lowest peaks with higher base as a result of increased subsurface flow due to irregular slopes and a poorly defined stream channel. The version of DHSVM used in this study simulates saturated flow from each pixel to the basin outlet separately using a convolution algorithm and combines these responses to determine basin outflow. The latest version of DHSVM, which includes an imposed channel network and allows reinfiltration of surface water, will be more sensitive to the errors observed in the low accuracy DEMs.

8.3 Conclusions

The DEM data currently available from radar and satellite imaging were found to be inappropriate for prediction of individual storm hydrographs but they could be applicable to large scale models or for bulk runoff volume predictions. The total predicted runoff volume depended on the average elevation and basin area of the DEM. This implies that the model calibration is dependent on the DEM. The spatial distribution of moisture fluxes and the predicted storm hydrographs for single events indicated that the SIR-C DEM could not properly represent the hydrologic behavior of the watershed.

The type of errors present in the SIR-C DEM did not indicate any particular source of error to be addressed, however the quantity of the errors necessitates higher resolution products to correctly simulate the hydrologic response of a basin to individual storm events or when peak flow volumes are of interest.

8.4 Recommendations for further research

On-going research for this project by others will compare TOPMODEL predictions with digital elevation data for a different study site. This will help to determine whether the results of the current study are independent of basin size, topography, vegetation and soil type. An investigation of prediction differences in areas of different climate would also be of interest. Topographic influences on estimations of solar radiation and snowmelt could be examined in a basin that develops a more significant snowpack.

Additional research on this topic could further investigate the expected vertical accuracy of DEMs. The standard USGS DEM used for this study was the lowest accuracy product available. Standard USGS DEMs of different classifications could be compared to give an indication of the reliability of the newer products. The SIR-C DEM used in this study was a preliminary product developed specifically for this project. The image processing should be finalized and compared to the preliminary product to assess any improvements in accuracy. A smoothing algorithm could be used to reduce the abrupt changes in

slope that are present in the preliminary DEM. The 50.5 m datum error in DEM should also be resolved to give a true indication of the basin elevations.

Improvements could also be made to the DHSVM representation of the surface flow in the Mahantango Basin. An explicit channel routing scheme would provide a more accurate definition of hydrologic processes on the watershed and would be more sensitive to differences in digital elevation data.

List of References

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Appendix A Fractal Dimension

The length of a coastline, measured by a rod of a specified length, varies with rod length according to a power law. The power of this relationship determines the fractal dimension of the coastline. Mandelbrot (1967) introduced the concept of a fractal based on this premise.

A.1 Definitions

The *fractal dimension*, D , is defined as:

$$N(x) = Lx^{-D} \quad (A.1)$$

where L is a distance along a surface or line which is measured in N discrete steps of length x . The value of D characterizes the intricacy or jaggedness of an entity where $D = 1$ defines a straight line, $D = 2$ defines a plane, and $D = 3$ is the dimension of independent random heights or spatial "white noise". Mandelbrot (1977) used the term *fractal* to refer to any geometric phenomenon with a fractal dimension greater than its topographic dimension and *fractional Brownian surface* to describe a class of single-valued fractal surfaces with $2 < D < 3$.

In a *self-similar fractal*, the phenomenon being measured is isotropic and results are independent of the orientation of the coordinate axes. In two-dimensional xy -space, a self-similar fractal $f(rx, ry)$ is statistically similar to $f(x, y)$ where r is a scaling factor. The fractal dimension of a self-similar fractal is constant. Topography is often self-similar in the horizontal dimension.

A *self-affine fractal* is anisotropic and the coordinates are scaled by different factors.

Topographic elevation is an example of self-affinity, the vertical coordinate is statistically related to the horizontal coordinate but has a systematically smaller magnitude. In two-dimensional space, $f(rx, r^Hy)$ is

statistically similar to $f(x,y)$ where H is the Hausdorff measure (Turcotte, 1992). The expected difference of the squared elevation difference between two points is given by:

$$E[(Z_p - Z_q)^2] \sim (d_{pq})^{2H} \quad (A.2)$$

where Z_p and Z_q are the elevations of the surface at points p and q , d_{pq} is the horizontal distance between the points p and q , and $H = (2 - D)$ in 1 dimension and $(3 - D_{2D})$ in two dimensions (Mark and Aronson, 1984).

A.2 Measurement techniques

A variety of methods have been suggested to calculate the fractal dimension of a surface. In a fractal and self-similar surface, the value of D should theoretically be in agreement regardless of the method used (Roy et al, 1987). In reality, natural surfaces depart from strict self-affinity and the differences among the algorithmic approaches and assumptions of the different methods of determining D are often so significant that comparisons of D values derived by different techniques are not valid (Lam and De Cola, 1993).

The ruler method or structured walk technique is the original method of measuring D and involves measurement of the number of steps corresponding to a given ruler length for a range of ruler lengths. D is then one minus the slope of a log-log plot of curve length (number of steps times ruler length) versus the ruler length (x-axis). For a two-dimensional surface, a series of profiles along the surface are measured and all data are plotted on one graph to determine D as two minus the slope.

The box method uses boxes to measure the curve and D is defined as the slope of the log-log plot of the number of boxes versus the inverse of the box size (x-axis). Surfaces are represented as profiles and

D is then one plus the slope. This method may be applied to non-isotropic surfaces by converting the squares to rectangles where the aspect ratio represents the ratio of the anisotropic scaling factor (Cox and Wang, 1993).

A.3 Variogram analysis

Mark and Aronson (1984) presented a variogram method to calculate the fractal dimension, D, of a topographic surface. The variogram is a measure of the spatial correlation of a regionalized variable. For this application, elevation was chosen as the regionalized variable. The variogram is then a function that describes the relationship between the mean-square difference of the elevations, z_p and z_q , and their intervening horizontal separation distance, d_{pq} .

The variogram, $2\gamma(h)$, and the semi-variogram, $\gamma(h)$, is mathematically defined by:

$$\gamma(h) = \frac{1}{2} \sum_{i=1}^n [z_p - z_q]^2 \quad (\text{A.3})$$

where h is equivalent to d_{pq} in all directions.

The method assumes that the image can be modeled as a fractional Brownian motion such that there is a distinct relationship between the distance between two pixels and the variance of the difference in the pixel values as described in Equation A.2. The variogram is the average variance of elevation versus the separation distance. On a log-log plot, the slope of the variogram, b, is equal to 2H. The fractal dimension, D_{2D} , is calculated as $3-(b/2)$.

The raw variogram for the Mahantango Creek research watershed was determined directly from the digital elevation data by calculating the separation distance and variance between elevation pairs within the basin. The watershed is defined by 8000 30 m pixels; the number of possible pairs is $(8000)(7999)/2 = 3.20 \times 10^7$. Instead of using all 8000 points, 200 points were randomly sampled selected from the data set. The separation distance and variance were computed between each combination

and the average variance was calculated for 10 separation ranges. This process was repeated 100 times, resulting in 100 average variance values for each range.

During the application of this technique, it was found that D changes with scale which suggests that self-affinity was only approached over restricted scale ranges and that an appropriate range of analysis should be selected.

A.4 Spectral analysis

Topographic data, z_{xy} , can be converted to the frequency domain in terms of its amplitude, h_{uv} , at different frequencies, Z_{uv} , by a Fourier transform. Two dimensional analysis may be based on Fourier transforms along profiles or on a two-dimensional discrete Fourier transform over the surface as suggested by Turcotte (1992). Using a 2D Fourier transform, the amplitudes in the frequency domain are defined as:

$$H_{uv} = \left(\frac{L}{N}\right)^2 \sum_{x=0}^{N-1} \sum_{y=0}^{N-1} z_{xy} e^{\left[-\frac{2\pi i}{N}(ux+vy)\right]} \quad (\text{A.4})$$

where u represents the transform in the x -direction ($u = 0, 1, 2, \dots, N-1$), v represents the transform in the y -direction, ($v = 0, 1, 2, \dots, N-1$), and N is the order of the equally spaced two dimensional square grid of linear size L . Each transform amplitude, H_{uv} , is assigned a radial wave number, k , as:

$$k = \frac{2\pi}{\sqrt{u^2 + v^2}} \quad (\text{A.5})$$

and the two dimensional power spectral density, S_{2j} , for each radial wave number k_j is defined as:

$$S_{2j} = \frac{1}{L^2 N_j} \sum_{i=1}^{N_j} |H_{uv}|^2 \quad (\text{A.6})$$

where N_j is the number of coefficients that satisfy the condition $j < (2\pi/k) < j + 1$ and the summation is carried out over all the coefficients H_{uv} in this range.

The dependence of the mean power spectral density on the radial wave number for a fractal distribution is:

$$S_{2j} \sim k_j^{-\beta-1} \quad (\text{A.7})$$

Equating the powers of Equations A.2 and A.7 yields $(-\beta-1) = 2H$ where $H = 3-D_{2D}$. The fractal dimension is determined from the slope of the log-log plot of the power spectral density function of power spectral density, S , versus the radial wave number, k as:

$$D = \frac{7-\beta}{2} \quad (\text{A.8})$$

The log-log spectral plots are not as linear as the plots derived using other methods and the slope is dependant on the selected range of the linear portion of the curve.

A.5 Fractal Dimension

The fractal dimensions of the standard and high resolution DEMs were determined using variogram analysis as discussed in Section A.3 and are displayed in Table A.1. The variogram for the 5 m high resolution DEM is displayed in Figure A.1. D of the fractally aggregated 30 m high resolution is higher than the D of the DEM aggregated by simple averaging. This is expected, as averaging acts as a low pass filter which will result in smoother the elevation data and a lower D . The D values are very similar for all the DEMs, differences are less than the expected accuracy of the variogram method.

Table A.1 Fractal dimension of DEMs

<i>DEM</i>	<i>grid size</i>	<i>aggregation method</i>	<i>D</i>
high resolution	5 m	n/a	2.385
high resolution	30 m	fractal interpolation	2.391
high resolution	30 m	simple averaging	2.390
standard USGS	30 m	n/a	2.399

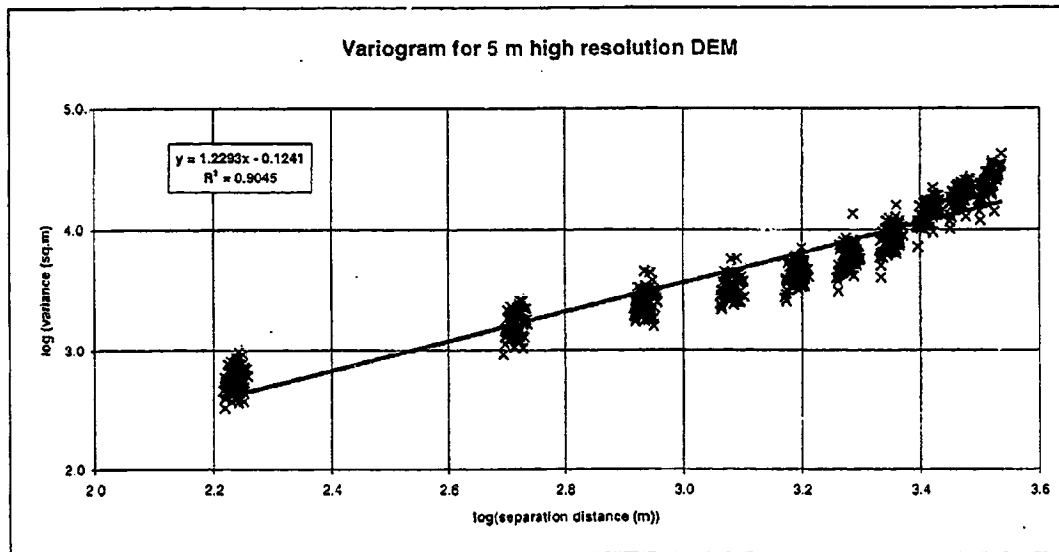


Figure A.1. Variogram for 5 m high resolution DEM

Appendix B Soil and Vegetation Classes

Table B.1 Overstory parameters

	<i>urban</i>	<i>tall vegetation</i>	<i>short vegetation</i>	<i>bare surfaces</i>
canopy attenuation coefficient	0.5	0.5	0.5	0.5
summer overstory leaf area index (LAI)	8.0	8.0	8.0	8.0
winter overstory LAI	2.0	2.0	2.0	2.0
overstory albedo	0.18	0.18	0.18	0.18
maximum overstory height (m)	15.0	15.0	15.0	15.0
exponential windspeed decay coefficient	1.5	1.5	1.5	1.5
displacement height ratio (d/h)	0.63	0.63	0.63	0.63
roughness length ratio (z/h)	0.13	0.13	0.13	0.13
max overstory fractional coverage	0.05	0.9	0.05	0.05
overstory maximum stomatal conductance (m/hr)	10.8	10.8	10.8	10.8
overstory minimum stomatal conductance (m/hr)	3.6	3.6	3.6	3.6
critical soil moisture content for overconductance	0.33	0.33	0.33	0.33
overstory light level	0.108	0.108	0.108	0.108
fraction of overstory roots in rooting zone 1	0.5	0.5	0.5	0.5

Table B.2 Understory parameters

	<i>urban</i>	<i>tall vegetation</i>	<i>short vegetation</i>	<i>bare surfaces</i>
summer understory LAI	1.0	1.0	2.5	1.0
winter understory LAI	0.1	0.1	0.1	0.1
understory albedo	0.1	0.2	0.23	0.1
maximum understory height (m)	0.1	0.1	1.5	0.1
vapor pressure deficit adjustment coefficient	1.0	1.0	1.0	1.0
understory max stomatal conductance (m/hr)	14.4	14.4	14.4	14.4
understory min stomatal conductance (m/hr)	0.72	0.72	0.72	0.72
critical soil moisture content for overconductance	0.13	0.13	0.13	0.13
understory light level	0.108	0.108	0.108	0.108
bare ground albedo	0.1	0.1	0.1	0.1
ground roughness length (z/h)	0.01	0.01	0.01	0.01
snow albedo	0.7	0.7	0.7	0.7

Table B.3 Soil Classes

<i>soil class</i>	<i>depth_1</i>	<i>depth_2</i>	<i>sat</i>	<i>conduct_exp</i>	<i>s_air</i>	<i>sk</i>	<i>field_cap</i>	<i>sm_wiltp</i>
1	0.25	0.25	0.501	0.19	0.21	0.03591	0.25	0.08
2	0.25	0.25	0.501	0.19	0.21	0.03591	0.25	0.08
3	0.25	0.25	0.501	0.19	0.21	0.03591	0.25	0.08
4	0.25	0.25	0.501	0.19	0.21	0.07315	0.25	0.08
5	0.25	0.25	0.501	0.19	0.21	0.05680	0.25	0.08
6	0.25	0.25	0.501	0.19	0.21	0.03591	0.25	0.08
7	0.25	0.25	0.453	0.19	0.15	0.08961	0.25	0.12
8	0.25	0.25	0.501	0.19	0.21	0.05680	0.25	0.08
9	0.25	0.25	0.501	0.19	0.21	0.08961	0.25	0.08
10	0.25	0.25	0.463	0.19	0.11	0.08961	0.25	0.12
11	0.25	0.25	0.501	0.19	0.21	0.05680	0.25	0.08
12	0.25	0.25	0.501	0.19	0.21	0.03591	0.25	0.12
13	0.25	0.25	0.501	0.19	0.21	0.08961	0.25	0.08
14	0.25	0.25	0.501	0.19	0.21	0.03591	0.25	0.08
15	0.25	0.25	0.501	0.19	0.21	0.07315	0.25	0.08

Soil parameters are defined as:

vpd_g_coef: vapor pressure deficit adjustment for the ground

depth_1: depth of rooting zone 1 (m)

depth_2: depth of rooting zone 2 (m)

sat: saturated water holding capacity or porosity

conduct_exp: m coefficient in Brooks-Corey (1/b from Campbell)

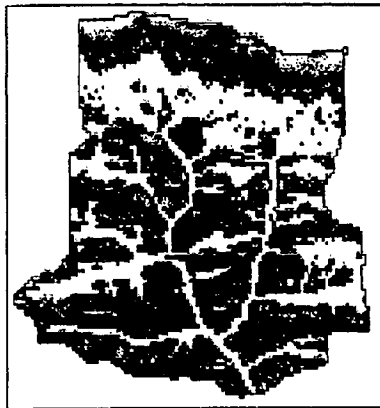
s_air: bubbling pressure of the soil (m of H₂O)

sk: vertical saturated hydraulic conductivity of the soil (m/hr)

field_cap: field capacity of the soil

sm_wiltp: wilting point of the soil

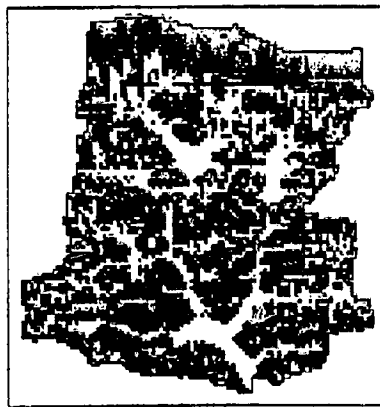
Appendix C DHSVM Spatial Predictions of Soil Moisture



Reference Depth to Saturation

average depth = 425 mm

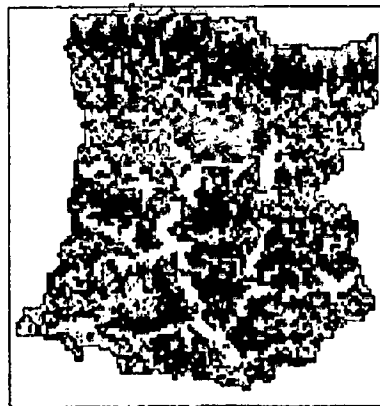
maximum depth = 825 mm



USGS Depth to Saturation

average depth = 471 mm

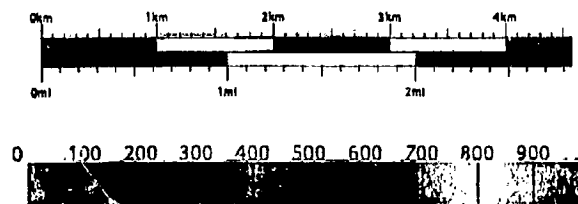
maximum depth = 867 mm



SIR-C Depth to Saturation

average depth = 540 mm

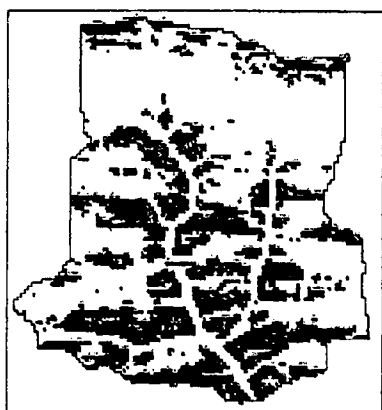
maximum depth = 921 mm



Depth to Saturation (mm) on Feb 13, 1985, 3 pm

Figure C1. Depth to saturation during high flow event of 1984/85 water year

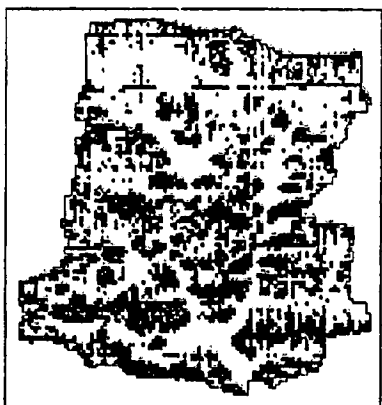
105



Reference Depth to Saturation

average depth = 200 mm

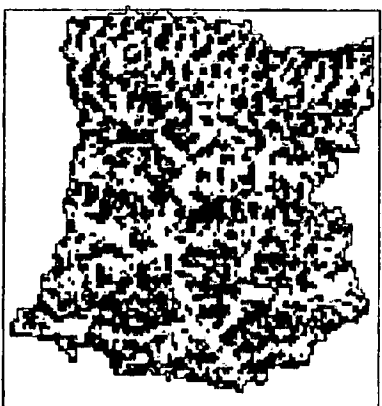
maximum depth = 626 mm



USGS Depth to Saturation

average depth = 234 mm

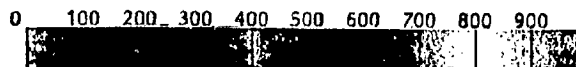
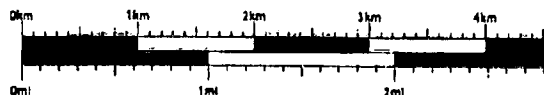
maximum depth = 677 mm



SIR-C Depth to Saturation

average depth = 298 mm

maximum depth = 894 mm



Depth to Saturation (mm) on Mar 15, 1986, 12 am

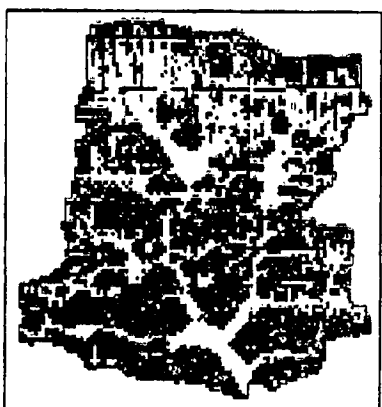
Figure C2. Depth to saturation during high flow event of 1985/86 water year



Reference Depth to Saturation

average depth = 266 mm

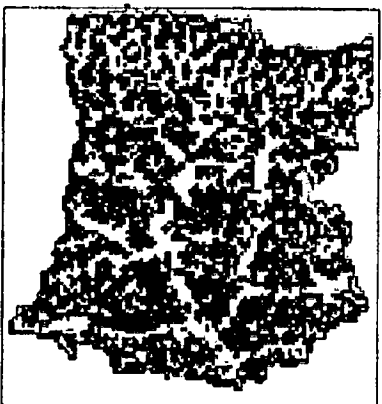
maximum depth = 585 mm



USGS Depth to Saturation

average depth = 288 mm

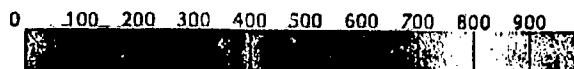
maximum depth = 674 mm



SIR-C Depth to Saturation

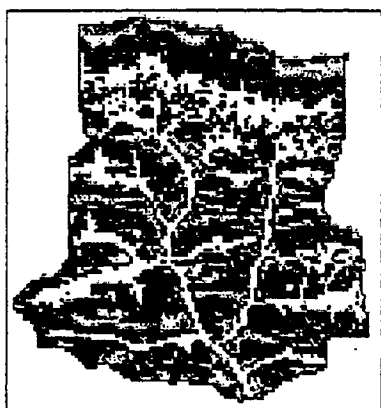
average depth = 331 mm

maximum depth = 951 mm



Depth to Saturation (mm) on Sep 14, 1987, 12 am

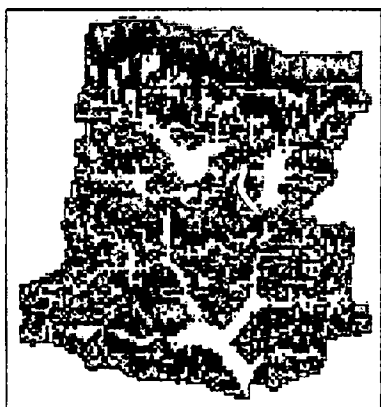
Figure C3. Depth to saturation during high flow event of 1986/87 water year



Reference Depth to Saturation

average depth = 447 mm

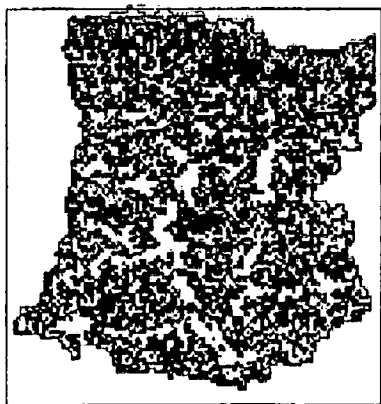
maximum depth = 984 mm



USGS Depth to Saturation

average depth = 538 mm

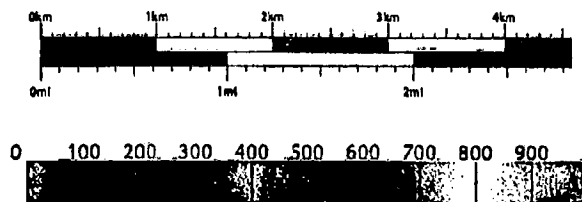
maximum depth = 999 mm



SIR-C Depth to Saturation

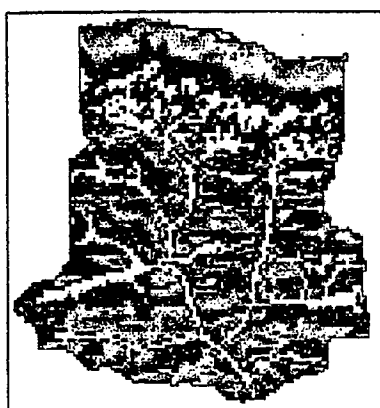
average depth = 628 mm

maximum depth = 1000 mm



Depth to Saturation (mm) on Jul 26, 1984, 12 am

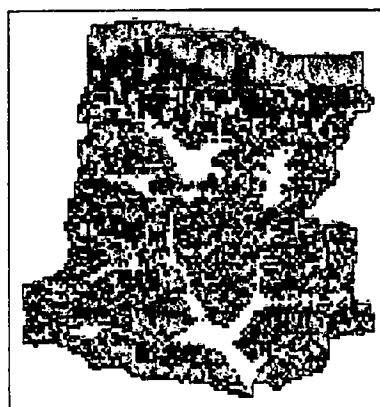
Figure C4. Depth to saturation during low flow event of 1983/84 water year



Reference Depth to Saturation

average depth = 597 mm

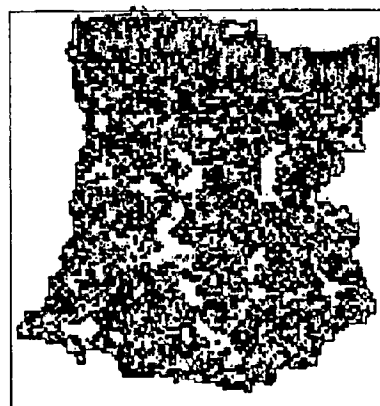
maximum depth = 192 mm



USGS Depth to Saturation

average depth = 66 mm

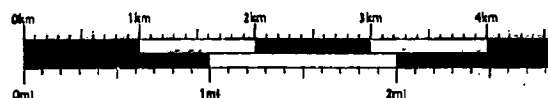
maximum depth = 999 mm



SIR-C Depth to Saturation

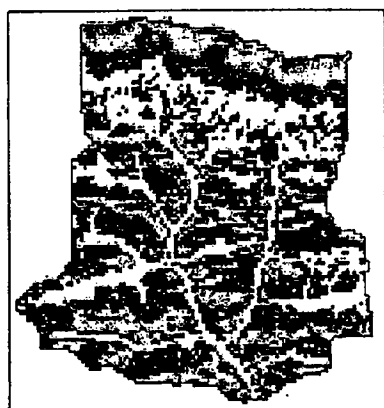
average depth = 725 mm

maximum depth = 1000 mm



Depth to Saturation (mm) on Aug 30, 1985, 12 am

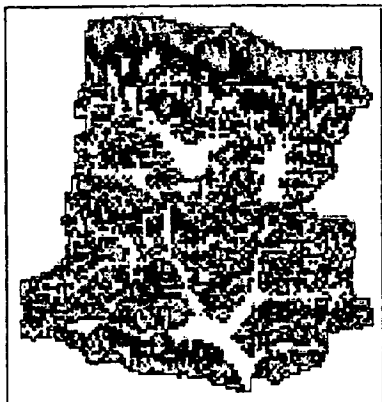
Figure C5. Depth to saturation during low flow event of 1984/85 water year



Reference Depth to Saturation

average depth = 549 mm

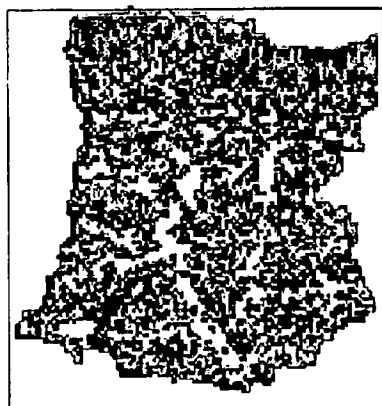
maximum depth = 988 mm



USGS Depth to Saturation

average depth = 615 mm

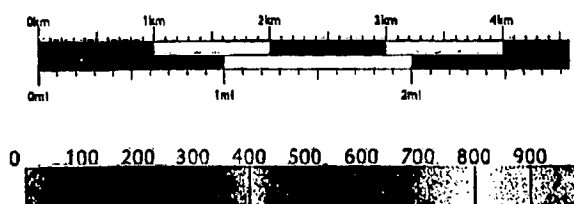
maximum depth = 999 mm



SIR-C Depth to Saturation

average depth = 697 mm

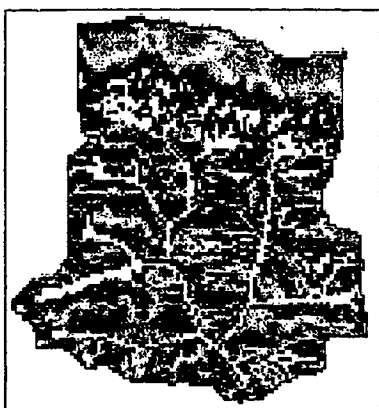
maximum depth = 999 mm



Depth to Saturation (mm) on Jan 15, 1986, 12 am

Figure C6. Depth to saturation during low flow event of 1985/86 water year

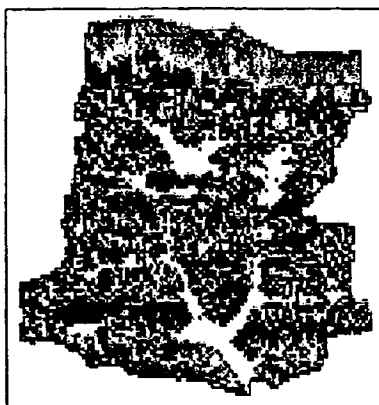
110



Reference Depth to Saturation

average depth = 672 mm

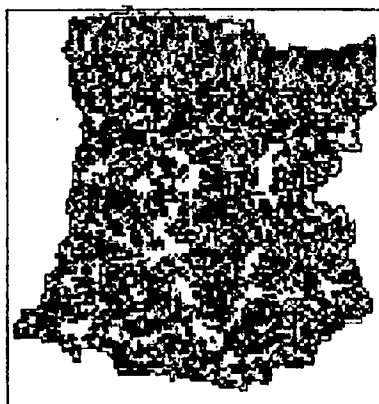
maximum depth = 997 mm



USGS Depth to Saturation

average depth = 741 mm

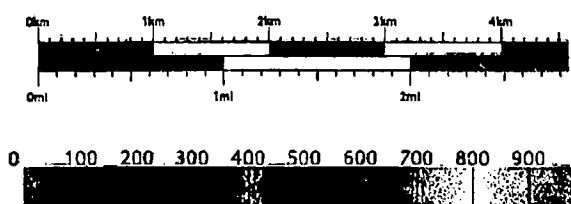
maximum depth = 999 mm



SIR-C Depth to Saturation

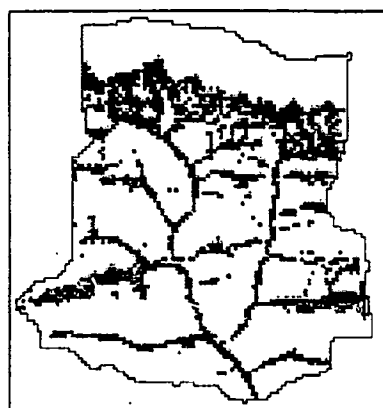
average depth = 789 mm

maximum depth = 254 mm



Depth to Saturation (mm) on Aug 5, 1987, 12 am

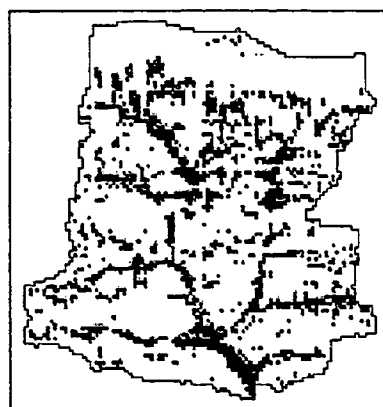
Figure C7. Depth to saturation during low flow event of 1986/87 water year



Reference Runoff Production

average runoff depth = 3.2 mm

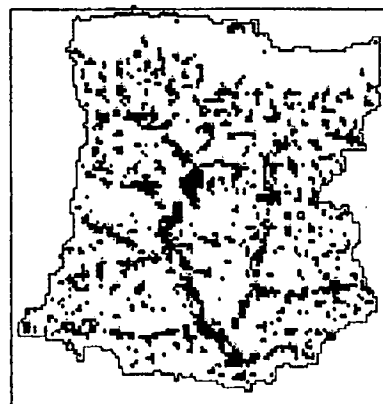
maximum runoff depth = 8.0 mm



USGS Runoff Production

average runoff depth = 3.2 mm

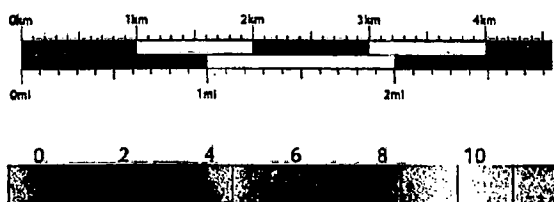
maximum runoff depth = 8.0 mm



SIR-C Runoff Production

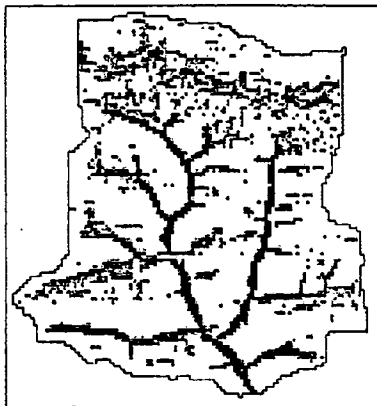
average runoff depth = 3.2 mm

maximum runoff depth = 9.0 mm



Runoff Production (mm) on Feb 13, 1985, 3 pm

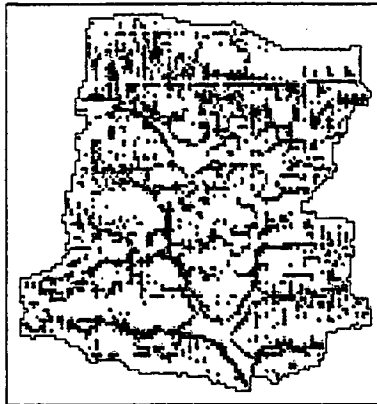
Figure C9. Runoff production during high flow event of 1984/85 water year



Reference Runoff Production

average runoff depth = 0.7 mm

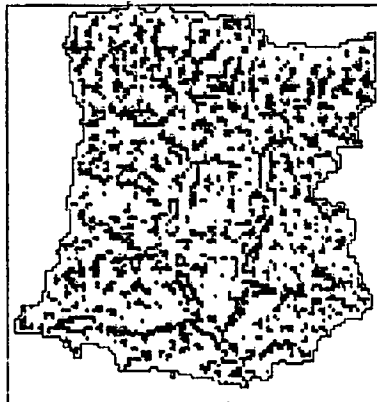
maximum runoff depth = 6.0 mm



USGS Runoff Production

average runoff depth = 0.9 mm

maximum runoff depth = 11.0 mm



SIR-C Runoff Production

average runoff depth = 1.3 mm

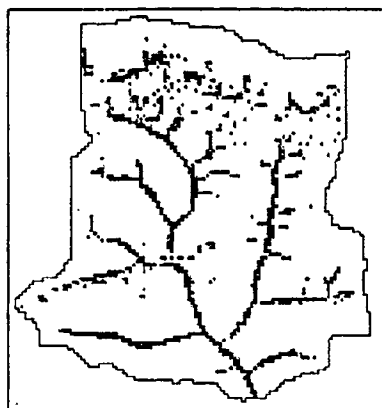
maximum runoff depth = 9.0 mm



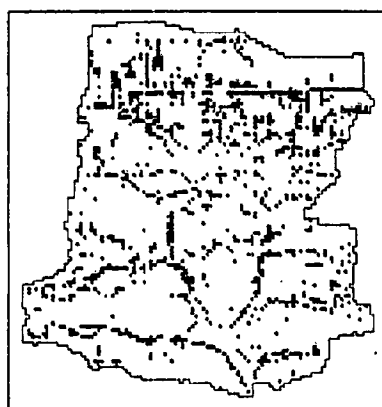
Runoff Production (mm) on Mar 15, 1986, 12 am

Figure C10. Runoff production during high flow event of 1985/86 water year

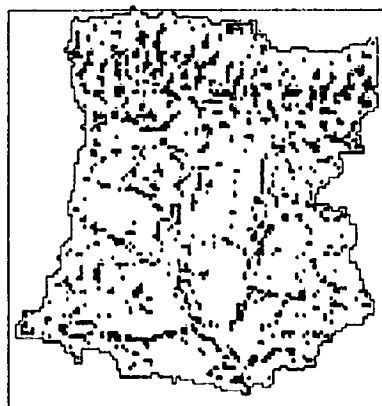
113

**Reference Runoff Production**

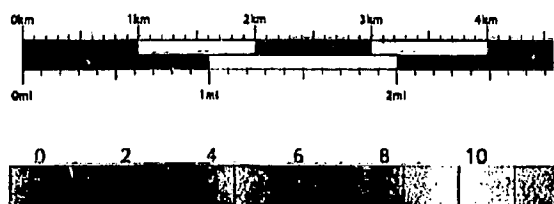
average runoff depth = 0.9 mm
maximum runoff depth = 4.0 mm

**USGS Runoff Production**

average runoff depth = 1.1 mm
maximum runoff depth = 9.0 mm

**SIR-C Runoff Production**

average runoff depth = 1.6 mm
maximum runoff depth = 10.0 mm



Runoff Production (mm) on Sep 14, 1987, 12 am

Figure C11. Runoff production during high flow event of 1986/87 water year

517

Appendix D DHSVM Time Series Predictions of Runoff

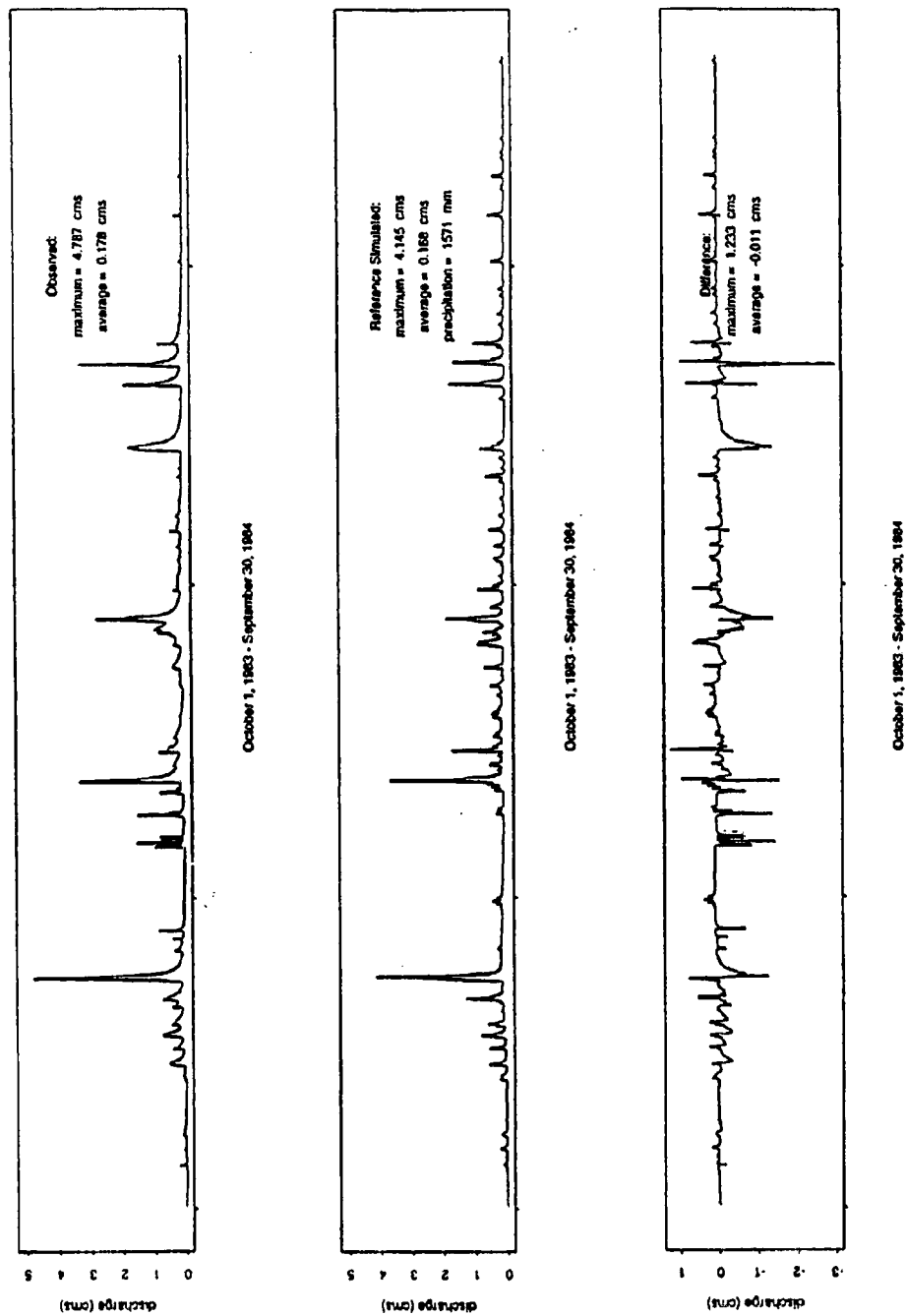
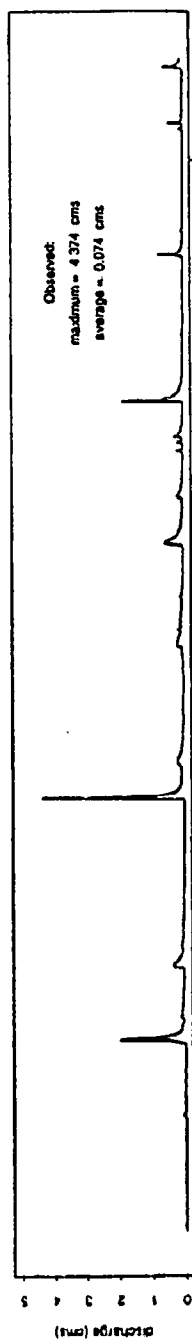
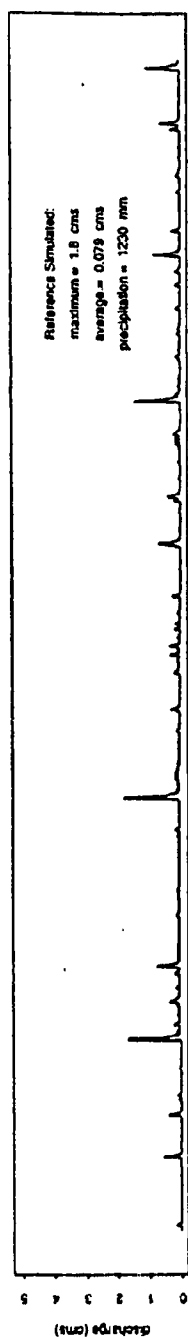


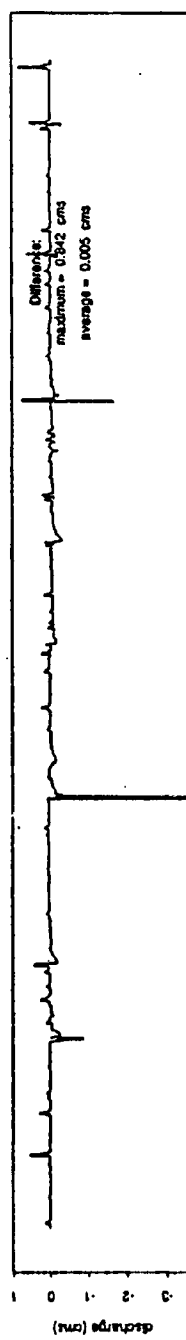
Figure D1. Calibration differences, 1983/84 water year



October 1, 1984 - September 30, 1985

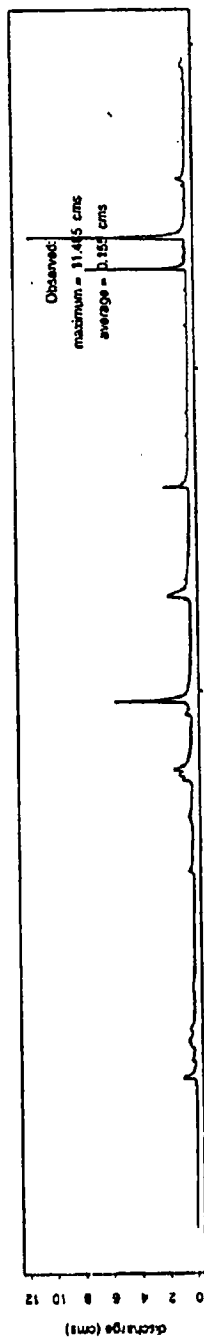


October 1, 1984 - September 30, 1985

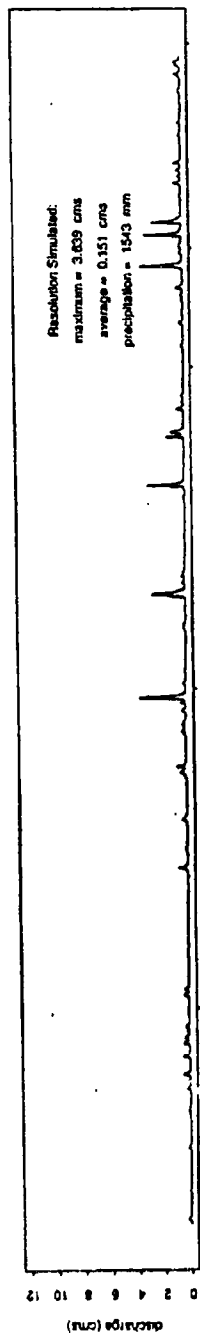


October 1, 1984 - September 30, 1985

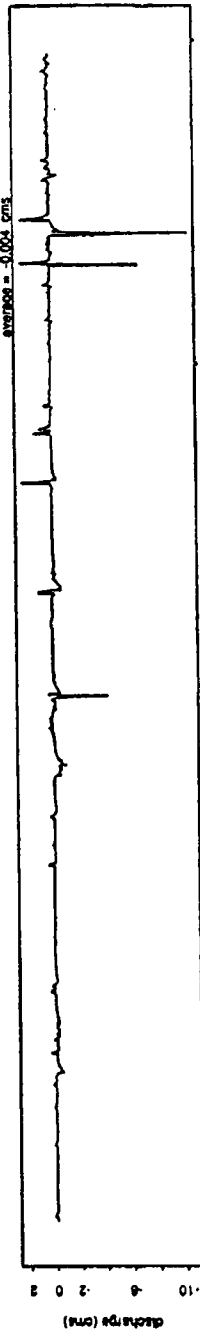
Figure D2. Calibration differences, 1984/85 water year



October 1, 1985 - September 30, 1986



October 1, 1985 - September 30, 1986



October 1, 1985 - September 30, 1986

Figure D3. Calibration differences, 1985/86 water year

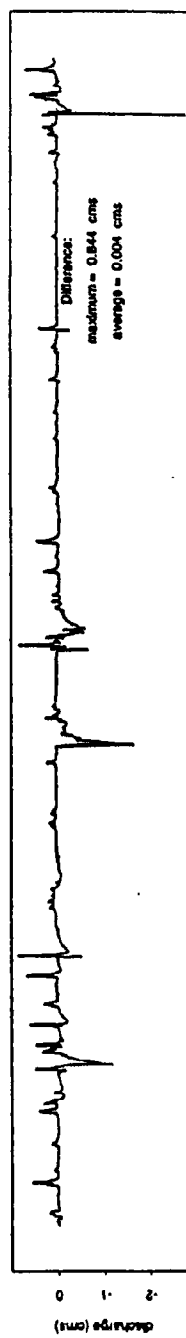
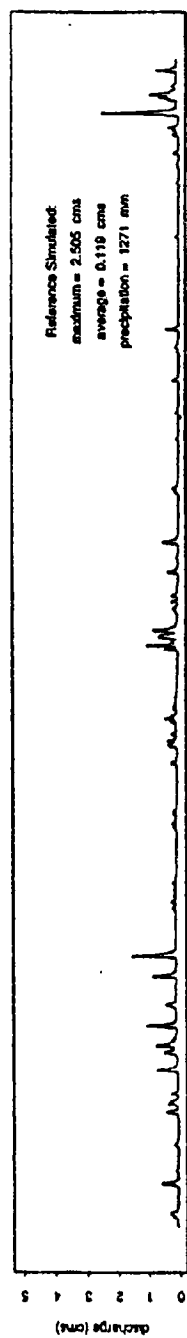
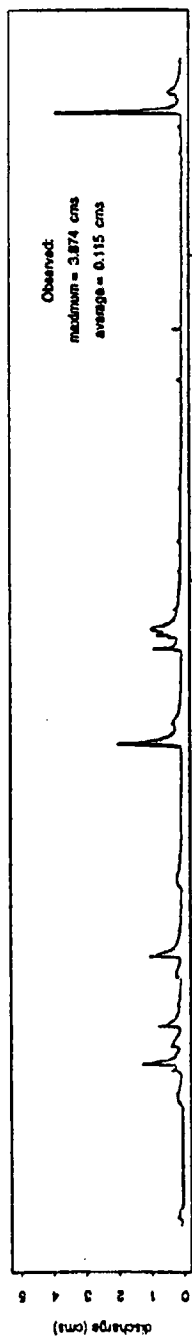


Figure D4. Calibration differences, 1986/87 water year

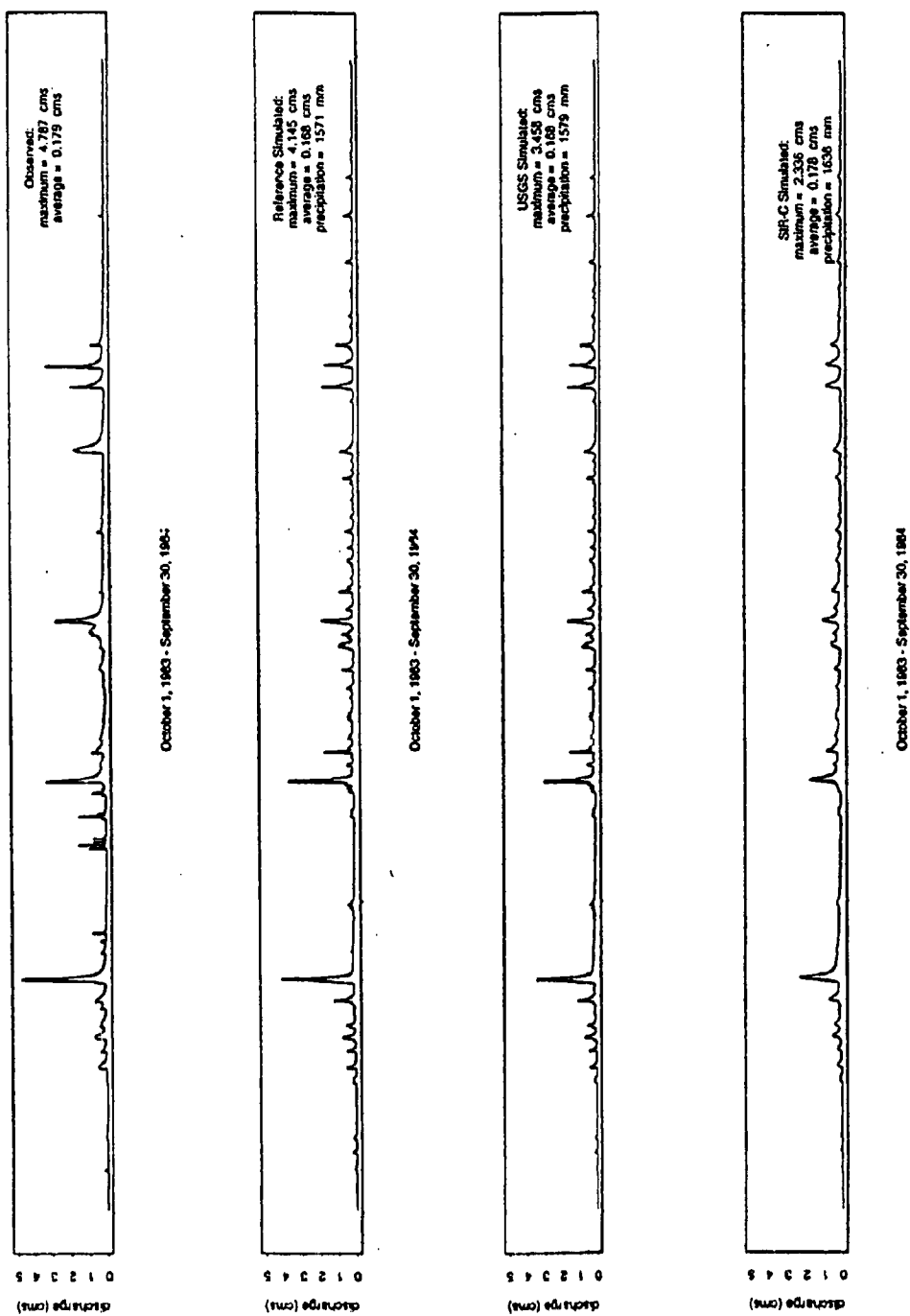


Figure D5. Predicted Runoff, 1983/84 water year

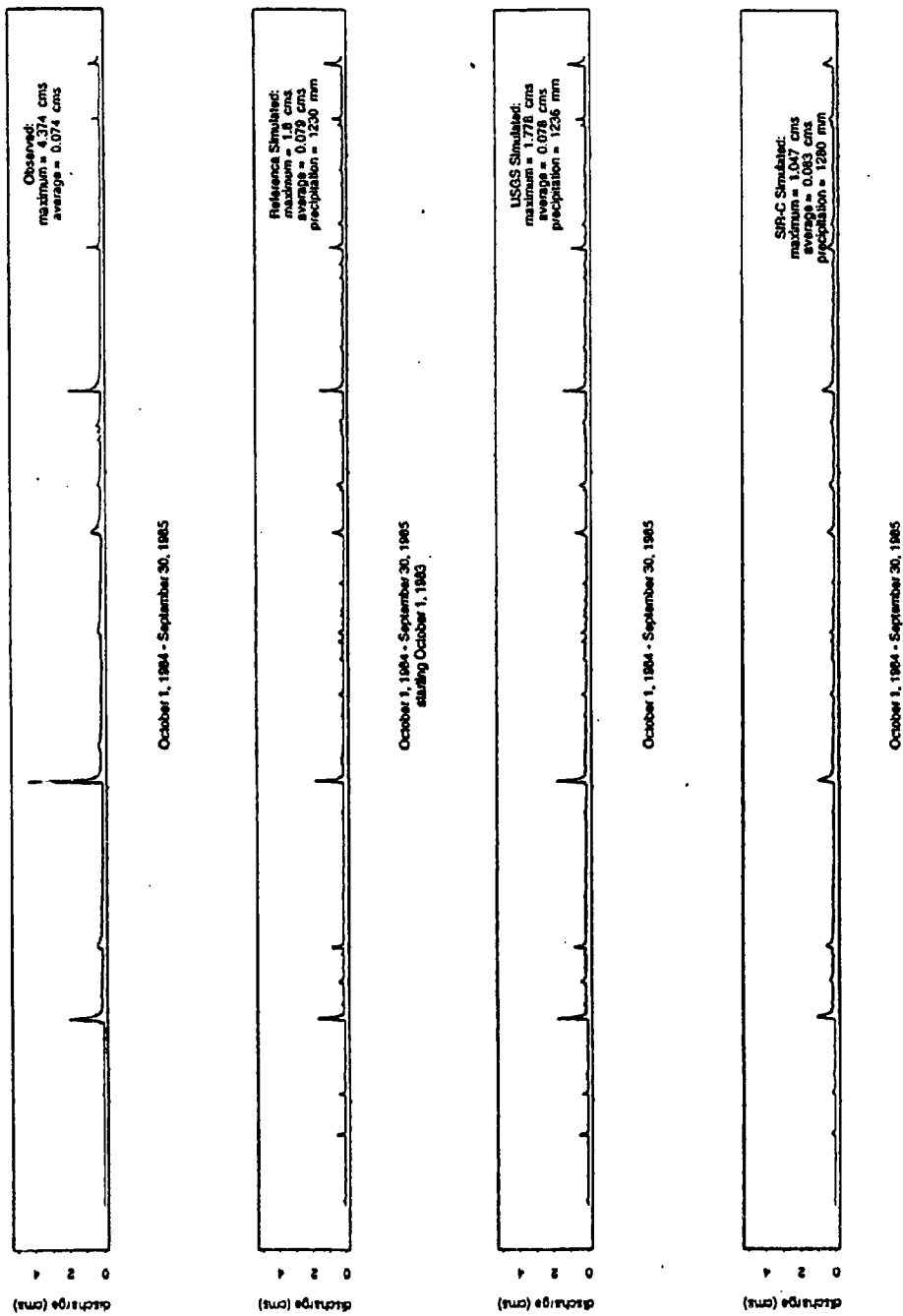


Figure D6. Predicted Kunoff, 1984/85 water year

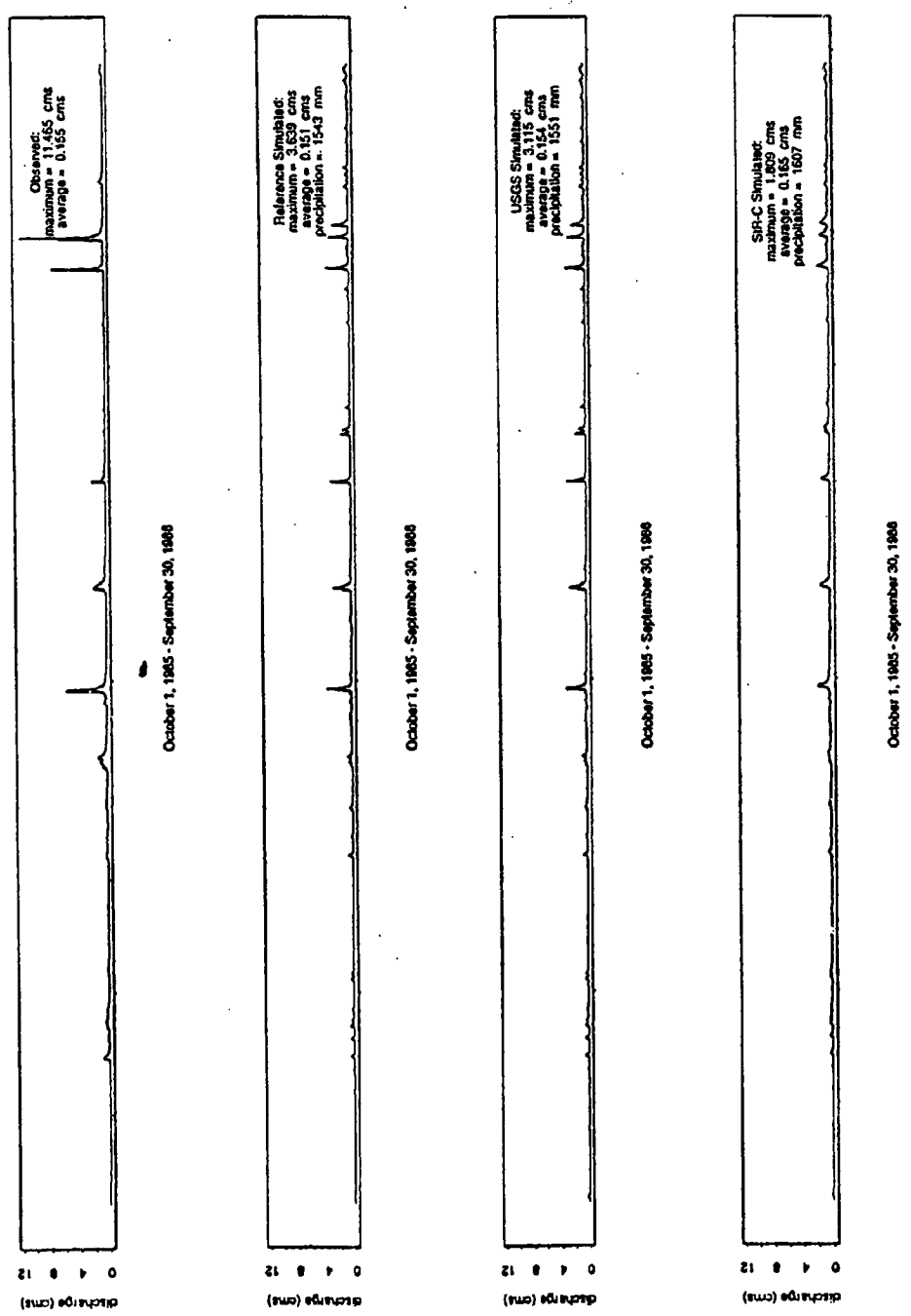


Figure D7. Predicted Runoff, 1985/86 water year

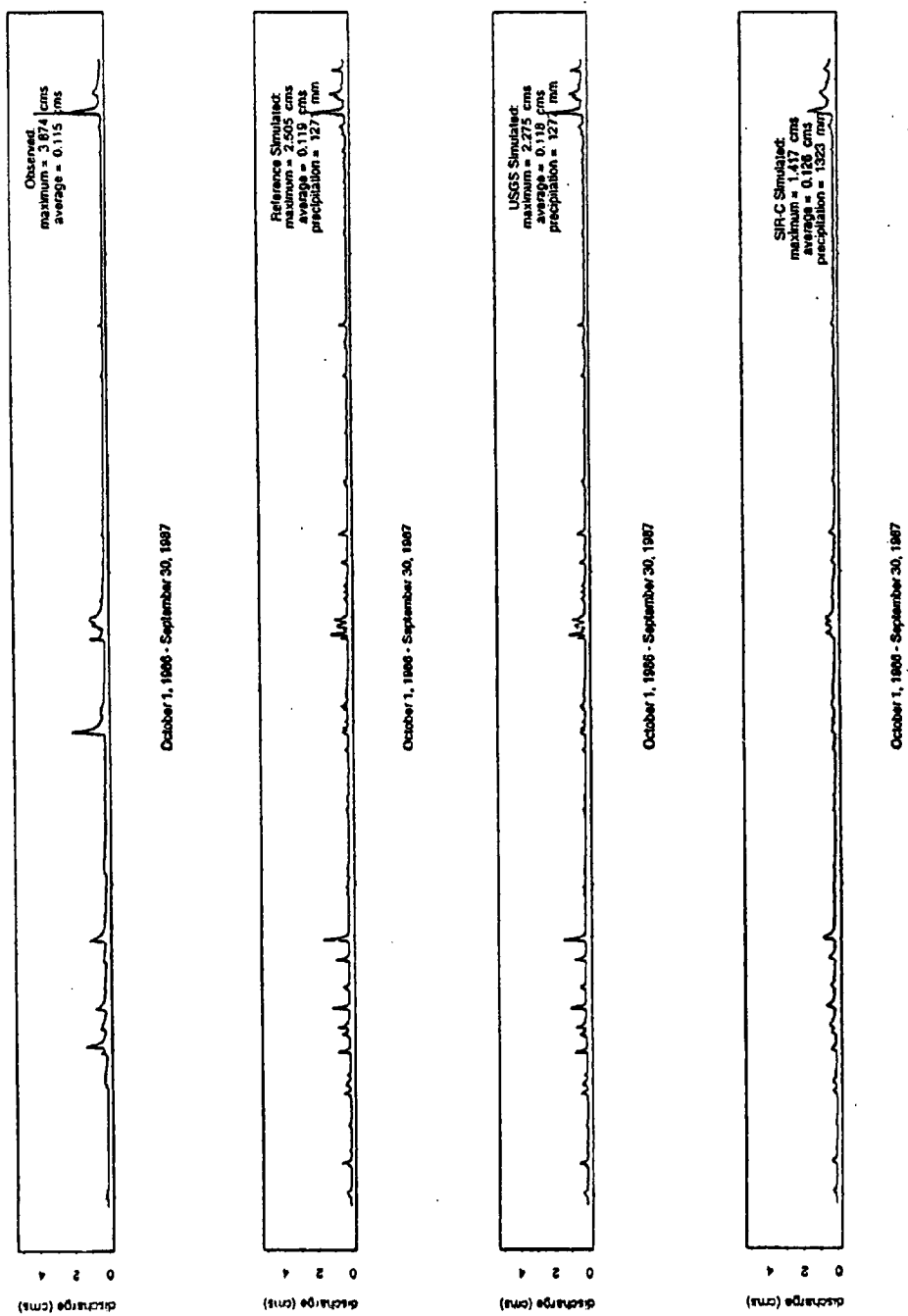


Figure D8. Predicted Runoff, 1986/87 water year

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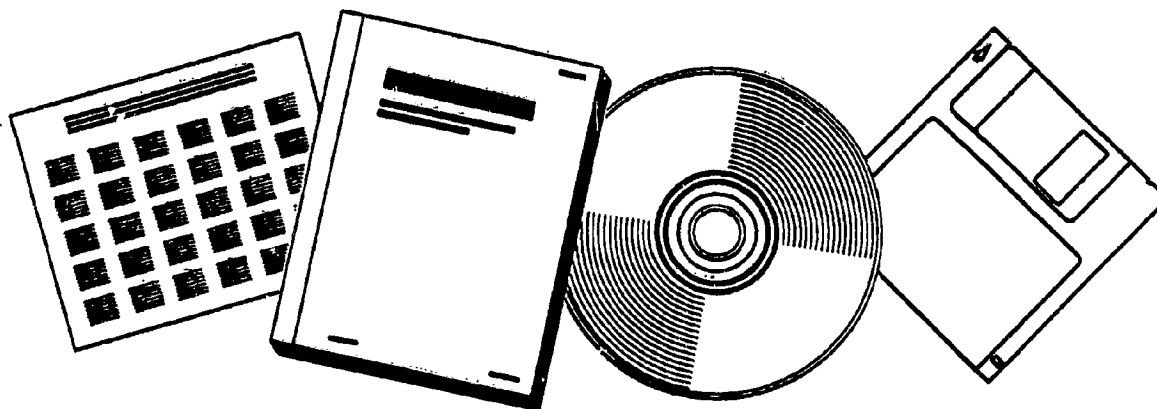
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EXAMINATION OF LABORATORY ACCREDITATION PROGRAMS IN THE UNITED STATES AND THE POTENTIAL ROLE FOR A NATIONAL LABORATORY ACCREDITATION SYSTEM

(U.S.) NATIONAL INST. OF STANDARDS AND TECHNOLOGY
GAITHERSBURG, MD

MAR 97



U.S. DEPARTMENT OF COMMERCE
National Technical Information Service



Examination of Laboratory Accreditation Programs in the United States and the Potential Role for a National Laboratory Accreditation System

Janice S. Jablonski
Consultant

Prepared for:

U.S. DEPARTMENT OF COMMERCE
Technology Administration
National Institute of Standards
and Technology
Gaithersburg, MD 20899

Grant 43NAN8709879

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Abstract: This report presents an initial study of existing U.S. laboratory accreditation programs, with a focus on government programs, particularly at the Federal level. The study was conducted in two phases: Phase I established categories of existing laboratory accreditation programs in the Federal government, at the state and local level, and in the private sector; Phase II compared technical standards used by the five Federal government laboratory accreditation programs with general standards for laboratory accreditation established by the International Organization for Standardization (ISO). The purpose of the study was to provide an initial assessment of the potential benefits of a national system for laboratory accreditation, particularly to existing Federal programs.

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ABSTRACT

On January 7, 1997, the National Institute of Standards and Technology (NIST), the American National Standards Institute (ANSI), and ACIL (formerly the American Council of Independent Laboratories) convened an open forum to present a proposed infrastructure for a U.S. laboratory accreditation system. The proposal, which would establish the National Council for Laboratory Accreditation (NACLA), is the result of a two-year effort by the three cosponsoring organizations to examine the viewpoints of industry, government and the public, characterize stakeholder concerns regarding the current system of laboratory accreditation in the United States, determine the need for a national system of laboratory accreditation, and develop a proposed infrastructure and implementation approach that would benefit users of laboratory accreditation and the public.

This report presents an initial study of existing U.S. laboratory accreditation programs, with a focus on government programs, particularly at the Federal level. The study was conducted in two phases: Phase I established categories of existing laboratory accreditation programs in the Federal government, at the state and local level, and in the private sector; Phase II compared technical standards used by five Federal government laboratory accreditation programs with general standards for laboratory accreditation established by the International Organization for Standardization (ISO).

The purpose of the study was to provide an initial assessment of the potential benefits of a national system for laboratory accreditation, particularly to existing Federal programs. The study supports two general conclusions:

- There are significant areas of overlapping scope, inconsistent program components, and application of highly variable accreditation terminology in laboratory accreditation programs in the United States; and
- Existing Federal government laboratory accreditation programs differ considerably in the extent to which they evaluate the general aspects of laboratory performance common to all testing and calibration laboratories.

Based on these conclusions, the study recommends that the NACLA Interim Board of Directors emphasize certain areas as it proceeds to develop a detailed plan for implementation.

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EXAMINATION OF LABORATORY ACCREDITATION PROGRAMS IN THE UNITED STATES AND THE POTENTIAL ROLE FOR A NATIONAL LABORATORY ACCREDITATION SYSTEM

1.0 INTRODUCTION AND BACKGROUND

This report presents the results of a study of laboratory accreditation programs operating in the United States. The study was conducted for the National Institute of Standards and Technology (NIST) to support the initial planning stages for a comprehensive national program for laboratory accreditation.

1.1 Background

The services of analytical testing and calibration laboratories support nearly every aspect of commerce and government oversight in the United States. Laboratory test data document the safety and efficacy of consumer products, foods and drugs, goods and materials used by public institutions, and of electronic and other devices used by the general public and by the government. For example, laboratory test data allow doctors to evaluate patient health and make diagnoses. They allow industry and the government to ensure that our water and air are not polluted, and they allow consumers to purchase products that are safe for use in their homes, schools and workplaces. Consequently, the reliability of laboratory test data affects virtually all aspects of public health and safety, and hence is an important public concern.

Laboratory accreditation programs have long been recognized as one means for providing uniform assurance that testing and calibration laboratories have the basic facilities, equipment, operating practices, and other characteristics necessary to generate reliable test data. Both industry and the government have recognized the benefits of accreditation programs, and many such programs now exist in both the public and private sectors.

The development of laboratory accreditation programs in the United States has occurred in response to specific needs in specific areas of commerce or government regulation. Programs are designed to address specific domestic or international problems and reflect the resource and other practical constraints of their specific industry, market, or government program. Consequently, there is not a single model nor a set of models for laboratory accreditation programs. Programs differ in terms of their administrative aspects, the scope and specificity of their standards, and the significance of the approval, certification or accreditation status conferred on laboratories. This independent "system" for laboratory accreditation in the United States has led both industry and the government to recognize that there is significant redundancy and inefficiency in the status quo. There is now a growing body of literature which addresses the trade and economic consequences of the current system and the need for a more coordinated approach to conformity assessment and laboratory accreditation.

Prompted in part by this growing recognition and in response to the American Technology Preeminence Act of 1991 (P.L. 102-245), the National Research Council (NRC) in 1994 convened a committee on International Standards, Conformity Assessment, and U.S. Trade Policy. The

Committee's final report, published in 1995,¹ called for steps to be taken to establish a comprehensive program for conformity assessment in the United States. Following publication of the NRC report, Congress and the President charged the National Institute of Standards and Technology (NIST) with responsibility for coordinating conformity assessment activities in the United States, under the National Technology Transfer and Advancement Act of 1995.

NIST in 1994 began working with the American National Standards Institute (ANSI) and ACIL (formerly the American Council of Independent Laboratories) to examine the issues and concerns associated with the current system for laboratory accreditation. The three organizations formed an informal public-private partnership to cosponsor the Laboratory Accreditation Working Group (LAWG), with the goal of developing an infrastructure for a national laboratory accreditation system that would meet the needs of both government and industry. Efforts were made to ensure participation by all government and private sector organizations with an interest in laboratory accreditation. In October of 1995, LAWG conducted its first open forum on national laboratory accreditation. The purpose of this forum was to receive public comment concerning identified problems caused by the current laboratory accreditation environment and the potential need for a national system. As a result of the 1995 open forum, several themes emerged to guide the work of LAWG:

- The present patchwork of laboratory accreditation activities in the United States is inefficient and costly.
- There is a general lack of confidence in U.S. accreditation systems in both the public and private sectors.
- There is a lack of widespread use of international standards as common baseline criteria by U.S. laboratory accreditation programs.
- Domestic acceptance of U.S. test data is complicated by the existing patchwork of multiple accreditation systems.
- International acceptance of test data generated in the United States is an important competitive issue.
- There is a compelling need to address these problems in a comprehensive and meaningful way.

During 1996, LAWG further examined the issues and concerns of the public and private sectors and began to develop a preliminary proposed structure and operating procedures for the National Council for Laboratory Accreditation (NACLA). LAWG completed a draft proposal for NACLA in

¹ See: National Research Council. 1995. *Standards, Conformity Assessment, and Trade Into the 21st Century*. National Academy Press. Washington, D.C.

the Fall of 1996.² The draft NACLA proposal reflects three principal problems with the current system, as follows:

Laboratory accreditation programs in the United States have developed independently over time. U.S. programs do not reflect a uniform minimum standard for design and operation; they do not utilize uniform terminology to describe the status of laboratories, nor do they utilize selected accreditors; and, typically, they do not recognize other accreditations through reciprocal agreements. As a result, there is considerable confusion with respect to the meaning or significance of different accreditations, certifications, approvals, and recognitions. There is also considerable overlap among programs. The inconsistency and overlap in programs and terminology creates inefficiencies and unnecessary costs and is a barrier to achieving international recognition of U.S. programs.

There is no focal point for laboratory accreditation programs in the United States. Lacking a central source of information and a forum for information sharing, cooperation, and reciprocity, government programs have invested in tools or systems that are redundant. Cases where government programs have achieved cost savings as a result of cooperative efforts are rare.

Some U.S. laboratory accreditation programs are not designed to meet international standards. Consequently, the process of achieving international recognition of testing data generated by U.S. laboratories is unnecessarily complicated and, in some cases, impossible. Establishing a focal point for laboratory accreditation in the United States would create the basis for coordinated participation in international laboratory accreditation cooperatives and would provide a single point of entry to the U.S. laboratory accreditation system for laboratories and accrediting authorities outside the United States. The overall effect would be a more accessible system of laboratory accreditation with broad international recognition.

In January of 1997, LAWG held a second open forum to present and discuss the NACLA proposal with a broad audience representing the range of public and private interests in laboratory accreditation. The 1997 open forum was attended by some 300 representatives of government, industry, the laboratory community and the private sector laboratory accreditation community. At the close of the forum, the participants agreed by a large majority that implementation of NACLA should proceed through the initial steps proposed by LAWG. Consequently, in February of 1997, LAWG elected an Interim Board of Directors for NACLA, with representation from industry, testing and calibration laboratories, the government, private sector accrediting bodies, and general interests. The Interim Board of Directors is expected to work for one year to develop an expanded proposal for NACLA's organizational structure and function, including a proposed constitution and bylaws. These documents are expected to be presented in a third open forum during 1998.

1.2 Purpose and Scope of This Study

The study described in this report involved collecting and analyzing information on existing laboratory accreditation programs. It was conducted to assist NIST and the future NACLA Interim

² See: Collins, Belinda. *Laboratory Accreditation: The Need for a National Infrastructure*. CalLab, November-December, 1996.

Board of Directors in developing an organizational structure and operating procedures for NACLA that:

- Take into account the missions and goals of individual laboratory oversight programs operated in the United States.
- Provide clear benefits to laboratory oversight programs in the public and private sectors so that maximum participation in and endorsement of NACLA by public and private stakeholders can be achieved.
- Serve as the basis for a system of continuous improvement in the conformity assessment process, both from the standpoint of cost-effectiveness and technical reliability.

The study involved two phases. Phase I resulted in an analysis of laboratory accreditation programs previously documented by NIST, which characterizes their purpose and scope and identifies the principal benefits that NACLA can offer them. Based on the information compiled in Phase I, five programs were selected for further analysis in Phase II. In this second phase, the five selected programs were examined to determine the extent to which their technical standards for accreditation are consistent with International Organization for Standardization/International Electrotechnical Commission (ISO/IEC) Guide 25: *“General Requirements for the Competency of Calibration and Testing Laboratories.”* This second phase provides an initial indication of the potential benefit to existing programs that would result from a NACLA accreditation based on the standards in ISO/IEC Guide 25.

1.3 Conclusions

The 1997 open forum provided a clear message from representatives of the private sector that there is strong support for a national system of laboratory accreditation. Supporters in the private sector cite the removal of international trade barriers and the potential for reduced costs and increased efficiency as reasons for establishing such a system. The potential benefits of a national system to government programs at the Federal and state levels are less well recognized, however.

This study provides an initial examination of existing government laboratory accreditation programs with the purpose of identifying some potential benefits to those programs that would result from a national system. While additional study and consideration of the implications of a national system are needed, this study supports some preliminary conclusions that may guide the deliberations of the NACLA Interim Board of Directors. They are as follows:

Some significant areas of overlapping scope, inconsistent program components, and application of highly variable accreditation terminology exist in laboratory accreditation programs. NACLA should include a process for addressing these aspects of the current system in a way that will strengthen and improve the overall U.S. laboratory accreditation system. Areas of overlap and inconsistency to be addressed should include:

- In the category of Federal programs supporting government oversight of product testing or certification, programs differ considerably in the

terminology used and the status granted to laboratories. Documentation of laboratory review procedures and criteria varies from program to program and program-qualifying procedures vary from simple review of written applications to comprehensive programs requiring written applications, on-site assessments, and routine laboratory proficiency testing.

- In the category of state and local programs supporting oversight of product testing/certification, preliminary information shows considerable overlap among state/local programs and Federal programs. Provisions for reciprocal recognition between programs were found in only a limited number of settings.
- Also in the area of product testing and certification, a large number of private sector programs appear to duplicate or overlap programs conducted at the Federal and state/local levels. Indications of cooperative or reciprocal relationships were identified in only a very few areas.
- In the area of state/local government programs supporting regulatory compliance, preliminary information shows that considerable overlap may exist between Federal and state programs and among state programs. Little evidence was found of reciprocal arrangements between state programs that accredit or certify for the same purpose. In the area of environmental testing, the National Environmental Laboratory Accreditation Conference (NELAC) has begun to address issues of overlap and to promote reciprocity among state programs. Similar problems in the area of occupational safety and health remain unaddressed, however.

Existing Federal government laboratory accreditation programs differ considerably in the extent to which they address the general aspects of laboratory performance common to all testing and calibration laboratories. These general areas include: laboratory organization and management, laboratory quality systems and audits, laboratory personnel, laboratory facility considerations, equipment and reference materials, measurement traceability and calibration, testing and calibration methods, handling of test items and specimens, laboratory record keeping, laboratory reports, subcontracting practices, and laboratory practices for addressing client complaints. NACLA should include a process designed to gain consensus among Federal government agencies concerning the value of ensuring that, at a minimum, all laboratory accreditation programs address these basic elements. NACLA should further set a goal of implementing such a minimum standard governmentwide reasonably soon. Ensuring that U.S. programs at a minimum address the components of ISO/IEC Guide 25 or its equivalent will improve the overall U.S. system and have both domestic and international benefits.

The NACLA Interim Board of Directors should consider NACLA to be an important leadership resource for the U.S. laboratory accreditation community in the future. For example, NACLA should develop and promote the application of the model used by NELAC and the National Conference on Weights and Measures (NCWM) to achieve consensus among existing, overlapping programs in other areas, particularly where state and Federal government programs overlap. There are many other examples of areas where NACLA leadership can be applied to improve

laboratory accreditation in the United States. For example, NACLA should serve as a forum for addressing issues common to numerous Federal government laboratory accreditation programs, such as:

- Proper procedures for ensuring due process in the suspension or revocation of an accreditation.
- Issues related to liquidated damages resulting from a loss of accreditation status for laboratories or loss of recognition status for accrediting bodies.
- Uniform standards for professional ethics in the accreditation process and in the laboratory industry.
- Appropriate roles for private accrediting bodies in areas typically addressed by government organizations.
- Appropriate relationships between private and public sector programs where they overlap.
- Uniform standards for maintaining confidentiality in the accreditation process and for identifying and addressing confidentiality violations.

Leadership within the Federal government would also provide a forum for identifying areas where cooperation among government programs or the establishment of public-private partnerships might be used to make existing laboratory accreditation programs more efficient and effective. Example areas include:

- Laboratory proficiency testing and related information management and dissemination needs.
- Development and distribution of reference materials for use by laboratories.
- Application of automated information management systems.
- Development and use of training programs.

The NACLA operating plan should therefore include provisions for bringing together representatives from all stakeholder groups to address these and other issues and develop consensus approaches to their resolution.

2.0 PHASE I: CATEGORIES OF EXISTING LABORATORY ACCREDITATION PROGRAMS IN THE UNITED STATES

This phase of the study consisted of a preliminary review of laboratory oversight programs conducted by the Federal government, state and local governments, and in the private sector. Individual programs in the public and private sectors were identified, briefly described and

categorized according to their common elements related to mission and purpose. This phase of the study was based on information from three principal sources:

- *Directory of Federal Government Laboratory Accreditation/Designation Programs*, NIST Special Publication 808 (February, 1991).
- *Directory of State and Local Government Laboratory Accreditation/Designation Programs*, NIST Special Publication 815 (July, 1991).
- *Directory of Professional/Trade Organization Laboratory Accreditation/Designation Programs*, NIST Special Publication 831 (March, 1992).

Information on each program listed in the directories was reviewed to identify: the purpose of the program, the scope of the program, the user community for the program, the laboratory community addressed by the program, and funding sources for the program. For each program in the Federal government, applicable Federal regulations were identified, searched and reviewed to further define the program's scope and purpose and to understand the roles of the government and private sector stakeholders in the program. In addition, conversations were conducted with representatives from some agencies to obtain information not otherwise available. Based on the information collected, programs in each major category (Federal government, state and local governments, and the private sector) were assigned to one of a series of categories based on their common mission-related elements.

Program Categories

Exhibit 1 summarizes the categories established for laboratory oversight programs operated by the Federal government, state and local governments, and the private sector. The remainder of this Phase I report provides a description of each category and lists the programs in each.

2.1 Federal Government Programs

Laboratory oversight programs operated by the Federal government have been established for three general purposes:

- To support procurement practices by government agencies.
- To support development of Federal regulations and enforcement of those regulations.
- To facilitate the international movement and/or sale of goods manufactured in the United States.

These three basic functions serve as the basis for the six Federal government program categories listed in Exhibit 1.

EXHIBIT 1
List of Categories for
Laboratory Accreditation Programs

Federal Programs

1. Programs supporting government procurement of analytical services
2. Programs supporting government procurement of goods and materials
3. Programs supporting generation of data for regulatory compliance demonstrations and regulatory decision making
4. Programs supporting government oversight of analytical services used by the general public
5. Programs supporting government oversight of product testing or certification
6. Programs supporting U.S. participation in international treaties or international trade interests

State and Local Programs

1. Programs supporting regulatory compliance determinations
2. Programs supporting oversight of product testing/certification

Private Sector Programs

1. Programs that overlap in scope with Federal or state government programs
2. Programs that have a unique scope and purpose

Programs supporting government procurement of analytical services

Numerous agencies of the Federal government purchase analytical services to support the implementation of their programs. The procedures by which contract laboratories are selected, laboratory performance is monitored, and laboratory reports are inspected and accepted constitute a laboratory oversight function which has all or nearly all of the components of a laboratory accreditation program.

The 1991 NIST Federal Directory lists only one such program. However, it is believed that this category is larger than indicated by the NIST Directory. One reason is that programs in this category may not be defined as formal laboratory "accreditation" or "approval" programs although they involve evaluation of laboratories against stated criteria for purposes of approval or acceptance. There are many examples of such programs in various stages of development and implementation. For example, in the past few years, efforts to remedy environmental hazards at Federal facilities have increased rapidly within the Department of Defense, the Department of Energy, and the Department of Interior. Each of these departments is in the process of establishing a system to oversee procurement of environmental analytical services needed to support their installation restoration efforts. While each department is at a different stage of designing and implementing a program that is tailored to its specific needs, these programs share

a common focus on evaluating laboratory quality systems to ensure that the necessary elements for reliable performance are present.

Environmental programs at EPA, DOD, DOE, and DOI are coordinated through a variety of intra-agency task forces and through the National Environmental Laboratory Accreditation Conference (NELAC). Through participation in NACLA, these agencies can benefit from working with their Federal and state peers who operate similar programs for different fields of testing by exploring opportunities for enhanced cost-effectiveness and identifying new tools and resources that may improve program efficiency and effectiveness.

The NIST Federal Directory identifies one formal program for accreditation or designation of laboratories to support government purchasing of analytical testing services:

The Department of Veterans Affairs Oversight Program for Veterans Administration Clinical Laboratories, which assesses and oversees physicians' diagnostic skills, histopathological services, and chemical, nuclear, and biological testing of clinical samples at VA facilities. Under this program, the College of American Pathologists inspects and accredits VA laboratories, working under contract to the Department of Veterans Affairs. The Veterans Administration Pathology Service oversees the contract. Physicians' diagnostic skills are monitored through the CheckPath quality control program operated by the American Society of Clinical Pathologists. In addition, the Armed Forces Institute of Pathologists monitors the VA histopathology program using a peer review approach involving physicians and medical technologists from the government and private sector to conduct assessments.

Presumably, every Federal government organization that purchases laboratory services conducts a formal or informal program for overseeing the performance of its participating laboratories. Examples of such programs include:

The Environmental Protection Agency's Superfund Contract Laboratory Program (CLP), which procures analytical testing services to support investigation and remediation of abandoned hazardous materials sites listed on the National Priorities List, under the Comprehensive Environmental Response, Compensation, and Liabilities Act (CERCLA). For this program, EPA qualifies laboratories responding to Invitations for Bid (IFBs), conducts periodic on-site assessments of laboratories performing under contract, and implements a regular program of quarterly laboratory performance evaluation testing. Contractors support certain administrative and technical program functions, such as routine screening of data packages delivered by the laboratories, invoice verification, and operation of the quarterly performance evaluation testing program. EPA staff are responsible for conducting laboratory assessments and inspecting/accepting deliverables. The CLP is EPA's largest program for procurement of analytical services. Other smaller programs conducted by the Agency generally do not have formal, documented procedures for laboratory oversight because they involve only a small number of laboratories.

Programs similar to EPA's Contract Laboratory Program are conducted by the Department of Defense and the Department of Energy to support oversight of laboratories that provide environmental analytical testing services for cleanup of Federal facilities in accordance with CERCLA. One such program is:

The Naval Engineering and Environmental Support Activity, Naval Facility Engineering Command Analytical Quality Assurance Program, which supports the Navy Installation Restoration (IR) program. Under the QA Program, NAVFAC assures the quality of environmental testing data collected to support cleanup of Navy facilities for purposes of compliance with CERCLA. As part of this program, NAVFAC operates an analytical laboratory evaluation program consisting of laboratory on-site assessments, proficiency testing, and data validation. All laboratories working under subcontract to engineering firms engaged in installation restoration activities for the Navy are required to participate in the program. Participating laboratories are evaluated to establish compliance with applicable Navy and EPA quality control and quality assurance requirements, as specified in a NEESA guidance manual (NEESA 20.2-047B).

The U.S. Army Corps of Engineers operates a similar program in conjunction with its Commercial Laboratory Assurance/Inspection Program (see category 2), and the Air Force Center for Environmental Excellence (AFCEE) also conducts a program for oversight of laboratories providing environmental testing services to support environmental clean-up activities at Air Force bases. The DOD and DOE programs rely on EPA's contract-specified methods and criteria to a significant extent and considerable coordination between the three agencies occurs routinely. Some coordination of these programs with EPA and with the states is occurring through NELAC.

Programs supporting government procurement of goods and materials

To ensure that goods purchased for the military meet specified standards, the Department of Defense has established centers such as the Defense Logistics Agency (DLA) and the Defense Electronics Supply Center (DESC). Laboratory oversight functions performed by these organizations are designed to identify testing laboratories capable of reliably performing routine specific tests designed to demonstrate that products meet standards for safety and durability. Many Federal government organizations require that goods and materials used by their programs meet published technical specifications to ensure the safety of users. These programs are often the Federal government equivalent of programs conducted at the state and local levels to ensure the safety of electrical equipment, building and construction materials and equipment, and fire prevention devices used by the general public.

The NIST Directory identifies such programs in the Department of Defense and the Department of Housing and Urban Development. Similar programs may exist in the Department of Energy, the Department of Interior, and other agencies of the Federal government. Identified programs include:

The U.S. Army Corps of Engineers District-Level Project and Commercial Laboratory Assurance/Inspection Program, which ensures that laboratories performing materials testing for the Corps of Engineers have the necessary capabilities. Under this program, District Engineers are responsible for ensuring

that the laboratories used in support of projects conducted by their Districts have the necessary capabilities. Corps of Engineers District Laboratory staff inspect and approve commercial laboratories working under contract. Corps of Engineers District Laboratories are evaluated regularly by the NIST Cement and Concrete Reference Laboratory. The scope of the program includes determination of capabilities for mechanical and chemical testing of soil, aggregates, stone, sand, cement-based products including lime, concrete and gypsum, building constructions (including foundations), water, air and other environmental media.

The DOD Defense Electronics Supply Center, which conducts a program to determine the suitability of laboratories equipped to perform specific testing for manufacturers listed on its Qualified Product/Qualified Manufacturers List (QPL/QML). Under this program, DESC engineers assess laboratories seeking to test military devices for compliance with applicable specifications. The scope of the program includes electrical, nonionizing radiation, metrology, nondestructive optical, and photometric testing of military devices.

The DOD Defense Logistics Agency Qualified Laboratory List identifies laboratories capable of performing specification tests for clothing, textiles, footwear, and equipment-type items used by the military. Under this program, personnel from the Defense Personnel Support Center testing facility conduct assessments of private laboratories to determine whether they qualify for the list. The list is intended to assist DOD contractors in identifying qualified laboratories performing chemical, electrical, nondestructive, optical, photometric, thermal and physical testing of textiles and equipment/apparel products to ensure compliance with military standards.

The HUD Federal Housing Administration Technical Suitability of Building Products Program accredits third parties that validate manufacturers' certifications of building materials used in all HUD projects. Independent validation of product certifications is required for all manufacturers that supply HUD projects. Under the program, HUD authorizes independent organizations as program administrators qualified to issue accreditations to independent laboratories. Approved administrators conduct their own accreditation programs for commercial laboratories. All Carpet Administrators are required to use laboratories approved for carpet testing by NIST's National Voluntary Laboratory Accreditation Program (NVLAP). As of 1990, there were approximately 30 approved administrators and 40 accredited laboratories.

There may be similar programs in other agencies that conduct extensive construction projects or purchase electronic and equipment and machinery, such as the Department of Energy, the U.S. Postal Service and the National Aeronautics and Space Administration (NASA).

Programs supporting generation of data for regulatory compliance demonstrations and regulatory decision making

Various agencies of the Federal government are empowered by Congress to implement regulatory programs designed to protect public health and welfare. These include the Department of Agriculture, the Department of Health and Human Services, the Department of Labor, and the Environmental Protection Agency, among others. These agencies require analytical testing data to support their regulatory programs for two purposes:

- Supporting the process by which the government determines what regulations are necessary and at what level to establish regulatory standards or criteria.
- Supporting the process by which compliance with regulations is monitored, violations are identified, and enforcement cases are developed.

Data required for these two purposes must achieve an established level of reliability and must be representative of conditions in the system being examined (e.g., the environment, a drinking water delivery system, or an industrial workplace). Consequently, laboratory oversight programs designed to support such regulatory functions are generally concerned with the broadest scope of data quality and may take into account the design and execution of sampling schemes and procedures, for example. Materials or media sampled and tested may be highly variable (e.g., wastewater effluent or hazardous waste) or sampling procedures may be complex and designed to capture a high degree of variability and/or very low and difficult to measure concentrations of analytes (e.g., ambient air). For these programs, laboratory accreditation is generally interpreted as a certification that an analytical system is capable of generating data of the required quality. Accreditation in this category generally does not provide any assurance of the reliability of individual measurements or data reports.

The Department of Agriculture, the Department of Health and Human Services, the Department of Labor, the Department of Commerce/National Institute of Standards and Technology, and the Environmental Protection Agency all implement laboratory oversight programs that address data generated to demonstrate regulatory compliance and/or to be used to support regulatory decision making. The NIST Directory identifies the following programs in this category:

The Department of Agriculture Food Safety and Inspection Service (FSIS) Laboratory Accreditation Program, which accredits domestic, nonfederal analytical chemistry laboratories that test meat and poultry products for moisture, protein, fat, salt, and chemicals, including chlorinated hydrocarbons, polychlorinated biphenyls, sulfonamides, nitrosamines, and arsenic for purposes of demonstrating compliance with Department of Agriculture regulations. FSIS personnel conduct laboratory inspections and laboratories are required to participate in a periodic proficiency testing program. Laboratories must demonstrate compliance with published requirements for personnel qualifications, test methods, quality assurance and record keeping (9 CFR 318.21). Analyses are conducted in accordance with methods published by the Association of Official Analytical Chemists. Data generated by laboratories in this program are used to support state and Federal enforcement programs. The program is open to all U.S. laboratories.

The Department of Health and Human Services National Laboratory Certification Program (NLCP), which certifies laboratories that provide drug-testing services to employers that are required to comply with Federal regulations regarding employee drug and alcohol testing programs. For example, the Department of Transportation requires that recipients of certain funding from the Federal Transit Administration (including railroads operated by the National Railroad Administration) maintain mandatory employee drug testing programs. The Nuclear Regulatory Commission requires that licensees authorized to operate nuclear power reactors or to possess, use or transport formula quantities of strategic special nuclear materials, implement programs for periodic testing of employees for drugs and/or alcohol. All laboratories used for drug-testing services by DOT and NRC units are required by Federal regulation to be certified under the NLCP (49 CFR Part 40 and 10 CFR Part 26).

The NLCP is open to all domestic and foreign government and private laboratories that seek to provide drug-testing services to support employee drug-testing programs required by Federal regulation. DHHS contracts with a private consulting firm for services to operate the program. The private firm conducts all administrative and technical aspects of the certification process. Laboratories pay a fee for certification directly to the contractor. DHHS staff oversee the performance of the contractor.

The DHHS/Food and Drug Administration Toxicology Laboratory Monitoring Program, which is designed to ensure the quality and integrity of safety data on drugs, food and food additives, human biological products and medical devices. Under the program, FDA staff inspect nonclinical laboratories to monitor and ensure compliance with its Good Laboratory Practices standards (21 CFR 58). Participation in the program is mandatory for laboratories that generate data for manufacturers of products requiring FDA approval. Under this program, FDA also performs laboratory assessments for EPA's laboratory oversight program conducted to support implementation of the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA).

The Environmental Protection Agency Lead Laboratory Certification Program, which certifies laboratories analyzing lead in paint, dust and soil samples to support elimination of lead-based paint hazards in housing. The program was implemented under authority of the Residential Lead-Based Paint Hazard Reduction Act of 1992. As directed by the statute, EPA has established performance standards for laboratories analyzing lead in paint, dust and soil samples. EPA utilizes third party accreditors to evaluate laboratories for certification and periodically publishes a list of accredited laboratories. The program supports regulatory compliance and enforcement activities conducted by EPA, HUD and the Department of Labor.

The Department of Labor Occupational Safety and Health Administration Blood Lead Program, which approves laboratories shown to be capable of meeting OSHA-specified accuracy requirements for analysis of lead in blood to support compliance with OSHA standards for lead exposures in the workplace (29 CFR

1910.1025). Under this program, OSHA approves laboratories based on their performance in a quarterly laboratory proficiency testing program. The program is open to all U.S. and foreign laboratories.

The NIST National Voluntary Laboratory Accreditation Program (NVLAP), which is a voluntary program to accredit public and private laboratories for conducting specified test methods or calibrations in several specific fields of testing and calibration, including accreditation for bulk and airborne asbestos fiber analysis, in support of EPA's asbestos program. NIST conducts the program for EPA in accordance with an Interagency Memorandum of Understanding.

The Environmental Protection Agency Drinking Water Laboratory Certification Program, under which laboratories that analyze drinking water to support compliance with the Safe Drinking Water Act are certified either by EPA or delegated state authorities. Under this program, EPA's Office of Research and Development National Exposure Research Laboratory certifies EPA's ten Regional Office laboratories for drinking water analysis. EPA Regional Certification Officers certify state laboratories and commercial laboratories located in states that do not have delegated programs. Delegated state Certification Officers certify commercial and utility laboratories that supply compliance data for drinking water systems within their boundaries. The program includes an annual mandatory program for laboratory proficiency testing.

Other EPA laboratory oversight programs which support regulatory and regulatory compliance programs include:

The FIFRA/TSCA Good Laboratory Practices Program, which assures the quality of data submitted by manufacturers requesting approval of chemical products under the Toxic Substances Control Act or pesticide products under the Federal Insecticide, Fungicide and Rodenticide Act. Under this program, FDA conducts audits of selected laboratories and studies for EPA. EPA also conducts its own audits of selected studies performed by laboratories not participating in the FDA program. In 1995, EPA committed to expanding this program to a full laboratory accreditation program by the year 2000.

The Discharge Monitoring Report Quality Assurance (DMRQA) Program, which conducts annual mandatory laboratory proficiency testing for laboratories supplying monitoring data in accordance with discharge permits issued under authority of the Clean Water Act. This program includes proficiency testing for chemical analysis and whole effluent toxicity testing. The program is designed to monitor compliance with the analytical testing and quality assurance requirements established under the Clean Water Act (40 CFR 136).

The ICR Laboratory Approval Program for drinking water laboratories participating in the Agency's Information Collection Requirements (ICR) Rule drinking water monitoring program. This program is operated by EPA's Office of Ground Water and Drinking Water separate from the Drinking Water Laboratory

Certification Program. It involves approving chemistry laboratories to perform specific chemical tests for disinfectants and disinfection by-products and approving microbiological laboratories for identification and quantification of *Giardia* and *Cryptosporidium* in drinking water samples, in accordance with EPA-specified methods. It includes a regular proficiency testing program. The ICR program was newly-established by EPA in 1995, and will run for a limited duration of approximately 2 years.

Programs supporting government oversight of analytical services used by the general public

In a few instances, Federal government programs have been established to oversee the quality of services provided by laboratories that serve the needs of the general public. The most significant example of this type of program is the Department of Health and Human Services program for certification of medical testing laboratories, which was established under the Clinical Laboratory Improvement Act of 1988. The most significant characteristic of these programs is that they encompass very large communities of laboratories that vary widely in terms of size and the range of services provided. Consequently, in addition to technical and scientific issues of quality control, these programs must address issues related to the impact of accreditation on both small and large laboratories, the wide range of compliance scenarios posed by diverse laboratory populations, and the administrative infrastructure required to oversee a large population. These programs require streamlined, efficient administrative and information management systems and must be based on policies reflecting trade-offs between financial and logistical considerations and quality objectives.

The NIST Directory identifies two Federal government programs established specifically to evaluate and approve laboratories that provide services to the general public:

The Department of Agriculture Animal and Plant Health Inspection Service Contagious Equine Metritis Program, which approves laboratories for conducting diagnostic procedures for venereal disease in horses (contagious equine metritis). Under the program, USDA Field Veterinary Medical Officers evaluate and approve laboratories. The program is open to all U.S. public and private laboratories.

The Department of Health and Human Services Health Care Finance Administration Clinical Laboratory Approval Program, which certifies all laboratories in the United States engaged in the testing of human specimens, under authority of the Clinical Laboratory Improvements Act of 1988. Originally, CLIA required the licensing of medical testing laboratories engaged in interstate commerce and certification of medical testing laboratories for Medicare or Medicaid payment status. In 1988, CLIA was broadened significantly to include all laboratories engaged in medical testing. This expanded program affects an estimated 300,000 to 600,000 laboratories.

Programs supporting government oversight of product testing or certification

This category is the largest of Federal government laboratory oversight programs. Programs in this category are generally designed to oversee independent testing laboratories that

perform specific, routine tests on designated products or types of products, such as electrical equipment, safety equipment and radio frequency emitting devices. Issues of sampling and sampling variability are less important (although not absent) in these programs. Programs in this category vary widely in terms of the terminology used and the "status" of laboratories reviewed. Some grant a formal accreditation or delegate authority to act on behalf of the government to qualified laboratories; others utilize only a "listing" process with no official relationship between the government and the laboratory (i.e., the applicable Federal regulations establish a process for manufacturers to apply for approval without provisions for a formal laboratory oversight or approval program). Consequently, this category provides an important opportunity for NACLA to serve as a vehicle for improving consistency and reliability in the conformity assessment community.

A large number of Federal agencies require that products or materials used for specific purposes be tested and certified to meet specific technical standards. For example, the Federal Communications Commission authorizes radio frequency emitting devices, the U.S. Coast Guard approves a variety of safety and other equipment used on board commercial and recreational vessels, the Department of Labor approves numerous types of electrical and other equipment as safe for use in the workplace, and EPA approves wood-burning stoves for use in the United States. All of these programs involve testing of products, generally by independent laboratories, to certify that they meet regulatory specifications. Such programs typically involve examination of test data and test facilities to determine that the laboratory is qualified to conduct the subject tests. In some cases, laboratories are specifically certified or accredited for the purpose; in others, the government maintains a list of qualified laboratories, but does not issue a specific certification or accreditation. This category of Federal government programs is by far the largest. The following 16 programs have been identified from the NIST Directory and other sources:

The Department of Agriculture Federal Grain Inspection Service, which approves private and government units to inspect and weigh grains and to test equipment and weights under the U.S. Grain Standards Act and approves Federal units to inspect and weigh commodities under the Agricultural Marketing Act. Under the program, USDA delegates authority to approved entities for purposes of conducting grain and commodity inspections and calibrating weighing equipment. The program is recognized by the National Conference on Weights and Measures.

The Department of Commerce National Conference on Weights and Measures State Laboratory Approval Program, which certifies state laboratories for compliance with standards established by the National Conference on Weights and Measures as part of a national program for uniform standards applicable to weighing and measuring devices. Through the NCWM, states develop uniform national standards which they then implement at the state level, by agreement. NIST evaluates state laboratories for compliance with the national standards, in accordance with the NCWM constitution and bylaws. Participation in NCWM is voluntary for states.

The Department of Commerce/NIST National Voluntary Laboratory Accreditation Program (NVLAP), which is a voluntary program to accredit public and private laboratories for conducting specific test methods or calibrations in specific fields of testing and calibration. NVLAP includes accreditation of

laboratories for conducting standard tests on products such as carpet, building materials (such as thermal insulation materials, concrete, cement, and aggregates), road/paving materials, radiation dosimetry devices, paint, paper, sealants, plastic, plumbing fixtures, and telecommunications equipment. NVLAP accreditation in these areas supports government programs for oversight of product testing or certification. NVLAP has other components (such as asbestos testing and fasteners and metals) that support regulatory programs.

The Environmental Protection Agency Wood Stoves New Source Performance Standards (NSPS) Laboratory Accreditation Program, which accredits laboratories for testing wood stoves to demonstrate their ability to meet New Source Performance Standards established by EPA under the Clean Air Act (40 CFR Part 60). Under the program, EPA staff conduct on-site laboratory inspections and award accreditation to qualified laboratories. Laboratories are then accredited to test and certify new wood-burning stoves, in accordance with EPA-specified methods. The program also includes an annual laboratory proficiency testing program.

The Environmental Protection Agency Program for Recognition of Independent Laboratories for Retrofit Device Evaluation, which recognizes independent laboratories as capable of performing screening tests on vehicles for assessing emissions and fuel economy benefits devices (including fuel additives). This program is intended to identify laboratories for use by manufacturers in conducting screening evaluations of products in advance of emissions testing conducted by the EPA laboratory. EPA staff evaluate written information received from laboratories. No on-site evaluation or proficiency testing is conducted. Laboratories having facilities and equipment similar to those of the EPA Motor Vehicle Emissions Laboratory are identified.

The Federal Communications Commission Program for Authorization of Radio Frequency Emitting Devices, which includes a program for listing laboratories capable of performing tests required for FCC authorization of equipment. Under FCC regulations (at the time of report preparation) governing the marketing of radio frequency devices, manufacturers are required to provide a description of the measurement facilities used to conduct the required tests (47 CFR 2.948). To support the review of measurement facilities information, FCC personnel maintain a list of qualified measurement facilities. Manufacturers use facilities listed by FCC to conduct required tests. FCC regulations provide for on-site inspections and witnessing of test procedures by FCC personnel; however, no routine program of on-site evaluations is conducted. Decisions to list laboratories are based on review of written information provided by laboratories. Laboratories are required to update the information on file with FCC as appropriate. Laboratories are "re-listed" every three years.

The Department of Health and Human Services, Food and Drug Administration Center for Food Safety and Applied Nutrition Evaluation of Milk Laboratories Program, which evaluates and endorses laboratories that

monitor milk and dairy products for biological and chemical contaminants. This program supports a voluntary consortium of FDA, the states, and the National Conference of Interstate Milk Shippers with the goal of ensuring the safety of dairy products sold in interstate commerce. Under the program, FDA and the states inspect milk laboratories periodically (every two or three years). Recognized laboratories participate in an annual split sample analysis program.

The Department of Labor Occupational Safety and Health Administration Nationally Recognized Testing Laboratories (NRTL) Program, which recognizes U.S. and foreign organizations capable of performing tests for safety on equipment and materials that meet OSHA-specified criteria. The program covers electrical and fire protection tests on electrical and related products used in the workplace. Criteria are specified as Federal regulation (29 CFR 1910). OSHA staff conduct all on-site laboratory evaluations. Accreditations are renewed every five years.

The OSHA Maritime Cargo Gear Accreditation and Certification Program, which approves third parties for purposes of inspecting maritime materials handling devices, such as cranes and derricks. This program covers mechanical, electrical, and nondestructive testing in accordance with specified methods and criteria. OSHA staff perform all laboratory evaluations. Laboratory approvals are renewed every one to three years. The program has international recognition through the International Labor Organization Convention.

The Department of Transportation/U.S. Coast Guard Merchant Vessel Inspection and Equipment Testing Program for Recreational and Commercial Vessels, which accredits laboratories for purposes of testing lifesaving, engineering, fire protection, and pollution prevention equipment used on recreational and commercial vessels to demonstrate compliance with Coast Guard standards. This program includes biological, chemical, mechanical, photometric, and thermal testing of safety, survival, fire protection and pollution prevention equipment. U.S. Coast Guard engineers assess and accredit laboratories to test and certify equipment in accordance with Coast Guard regulations.

The U.S. Coast Guard Program for Approval of Equipment Used in Hazardous Areas Aboard Commercial Vessels, which recognizes independent testing laboratories for testing of electrical equipment used in hazardous areas on Coast Guard certified vessels. This program involves approval for conducting electrical, mechanical and nondestructive tests on electrical enclosures, wiring and cabling, in accordance with standards established by the National Electrical Code and the National Fire Protection Association. Under this program, U.S. Coast Guard engineers conduct all laboratory evaluations.

The Department of Treasury U.S. Customs Service Petroleum Laboratory Accreditation Program, which accredits laboratories for the purpose of conducting chemical testing of petroleum, petroleum products, and bulk organic chemicals upon entry to the United States to determine that they meet standards established by U.S. Customs (19 CFR 151.13). All tests are performed in accordance with ASTM

and American Petroleum Institute methods and standards. U.S. Customs personnel conduct all laboratory evaluations.

Programs supporting U.S. participation in international treaties or international trade interests

In a small number of cases, agencies of the Federal government have established laboratory oversight programs in response to requirements imposed by the international community related to products exported from the United States. In these cases, in order to maintain the position of U.S. commerce abroad, the government has entered into formal treaties that require establishment of a laboratory accreditation or certification program or simply created a government program to certify laboratories in response to import restrictions implemented by foreign governments.

The NIST Directory identifies three laboratory certification programs which are conducted for purposes of testing products exported from the United States or used in export activities. These are:

The Department of Agriculture Program for Certification of ATP Test Stations and Laboratories, which certifies facilities that test trucks, trailers, rail cars, freight containers, refrigeration units, and other equipment used for international transport of perishable foods, as required by the Agreement on International Carriage of Perishable Foodstuffs. Department of Agriculture staff conduct all evaluations under this program. Certified facilities are authorized to issue ATP certificates for equipment determined to meet established standards. As of 1990, 20 countries were signatories to the Agreement.

The U.S. Coast Guard Cargo Container Safety Approval Program, which approves organizations to conduct mechanical tests on cargo containers used in international shipping for purposes of compliance with the International Convention for Safe Containers. Under this program, Coast Guard personnel review and approve third parties to receive delegated authority from the Commandant of the Coast Guard to approve containers for use in international shipping. The program is open to all U.S. laboratories and laboratories in foreign countries that are not parties to the Convention.

The Department of Treasury Bureau of Alcohol, Tobacco, and Firearms Laboratory Certification Program for Analysis of Wines and Distilled Spirits, which certifies laboratories that analyze wine and distilled spirits to meet the requirements of foreign governments for exported products to be accompanied by a chemical analysis generated by an ATF-certified laboratory. Analyses are required to be conducted in accordance with Internal Revenue Service and ATF procedures. ATF personnel assess written documentation from laboratories. No on-site evaluation or proficiency testing is required.

2.2 State and Local Government Programs

Programs Supporting Regulatory Compliance Determinations

Under numerous Federal statutes, regulatory programs may be delegated to states upon a finding that the state program is equivalent to the Federal program. In cases where the Federal program includes a laboratory oversight function, state programs must also include an equivalent laboratory function. Under all of the major regulatory programs implemented by EPA, for example, authority is delegated to equivalent state programs to enforce the Federal program. In the case of drinking water programs, all delegated states are required to certify laboratories that provide drinking water monitoring data for compliance purposes. State certification programs must be based on Federal guidance and may rely on EPA's national laboratory proficiency testing program, or they may rely on another, equivalent proficiency testing program that meets their specific needs. Under the Clean Water Act, state programs must require that all facilities classified as Major Dischargers participate in EPA's annual laboratory proficiency testing program for chemistry and whole effluent toxicity testing. In the areas of hazardous waste and air quality, EPA's Federal programs do not have specific provisions for laboratory accreditation. States with delegated programs in these areas are therefore not required to certify laboratories for hazardous waste or air analysis. However, many states have developed certification programs in these areas, especially where they can be easily added as an expansion to existing drinking water laboratory certification programs. All of these environmental programs are coordinated on a national level through the National Environmental Laboratory Accreditation Conference.

States also implement their own occupational safety and health programs. All regulated industries are required to comply with the Federal regulations established by OSHA. Some states also have their own additional requirements. All equipment testing laboratories used by manufacturers of workplace equipment must be recognized by OSHA's NRTL Program, at a minimum. State programs may rely on the NRTL Program or may have their own mandatory, independent laboratory approval or accreditation process.

In addition to regulatory programs delegated by the Federal government, states operate regulatory programs in accordance with authorities established solely by state statutes. Such programs may also include laboratory accreditation or oversight programs. For example, state programs for oversight of weights and measures activities (i.e., those participating in the National Conference on Weights and Measures).

The following laboratory oversight program types have been identified at the state and local level to support enforcement of regulatory programs:

Drinking Water Laboratory Certification Programs: All states having delegated authority to enforce the Federal Safe Drinking Water Act certify laboratories that analyze drinking water for compliance purposes. States have designed their own laboratory certification programs, developed their own standards and criteria for certification, and require the use of either an EPA-operated laboratory proficiency testing program or an alternative program. All state programs are based on technical guidance provided by EPA. State Certification Officers are required to

attend an EPA training program and state drinking water laboratories are certified by the EPA Regional Laboratories.

Wastewater Laboratory Certification Programs: Some states with delegated authority to enforce the Clean Water Act operate certification programs for wastewater laboratories. These programs are typically administered in conjunction with the state's drinking water laboratory certification program and utilize EPA proficiency testing programs for wastewater analysis. Because there is no national laboratory accreditation program for wastewater laboratories (the DMRQA program noted previously only requires participation in an annual laboratory proficiency testing study), no EPA guidance is provided for such programs. Guidance addressing laboratory inspections is available from EPA, however.

Hazardous Waste Laboratory Certification Programs: A smaller number of states operate laboratory certification programs for laboratories conducting analyses to document compliance with state Resource Conservation and Recovery Act (RCRA) programs (with delegated authority from EPA) and for state programs designed to provide for remediation of abandoned hazardous materials sites that are not listed on the National Priorities List. Since EPA does not operate laboratory certification programs in either the RCRA or Superfund areas, there are no Federal requirements or guidance for such state programs. Analytical method guidance is provided by EPA for RCRA compliance and the methods used by EPA's Superfund Contract Laboratory Program are often used by state programs. EPA does not conduct a national laboratory proficiency testing program for hazardous waste analysis. States may use results from the drinking water and/or wastewater proficiency testing programs, or they may require that laboratories purchase studies from private vendors. In a small number of cases, states produce and distribute their own performance evaluation studies.

Air Quality Laboratory Certification Programs: A small number of states also operate laboratory certification programs for laboratories conducting analyses to support compliance with the Clean Air Act. These programs exist only in the few states that have comprehensive environmental laboratory accreditation programs. EPA does not have a national program for accreditation of air quality laboratories, and state programs are designed to meet the needs of the state program, utilizing analytical methods guidance published by EPA. EPA does operate national proficiency testing and reference materials programs for air quality laboratories, which are utilized by state programs.

Comprehensive Laboratory Certification Programs Supporting Implementation of State Sanitary Codes: Several states operate comprehensive laboratory accreditation programs to support areas regulated under state sanitary codes. These programs oversee, for example, veterinary laboratories, animal research laboratories, and certain product testing laboratories. Many also include the state drinking water laboratory certification program under the umbrella sanitary code program.

Programs supporting oversight of product testing/certification

Nearly all states have laboratory oversight programs for laboratories that test products and materials for certification under state and local laws. Some of these programs overlap with programs at the Federal level. For example, while the majority of occupational safety and health programs at the state and local levels rely on OSHA's Nationally Recognized Testing Laboratory (NRTL) Program, some jurisdictions have their own laboratory accreditation or recognition programs that are specified in addition to the OSHA NRTL Program. Others evaluate laboratories for the same fields of testing as Federal programs, such as the Department of Defense program for certification of electrical equipment and the Department of Housing and Urban Development program for certification of building and construction materials. This overlap represents another significant opportunity for NACLA to make the current system of laboratory accreditation and conformity assessment in the United States more consistent and efficient. Following is a listing of types of programs in this category that have been identified at the state and local level from the initial information sources.

Laboratory approval related to fire safety products/materials certification (pertaining to products listed by state/local Fire Marshals)

Laboratory approval related to testing buildings (including foundations) for compliance with earthquake standards (identified in California only)

Laboratory approval related to products or equipment used in the workplace

Laboratory approval related to testing solar collection devices (identified in Florida only)

Laboratory approval for testing dairy products

Laboratory approval for testing other types of foods

Laboratory approval for testing electrical materials, devices and appliances based in the National Electrical Code

Laboratory approval for testing products covered by state sanitary codes, including disinfectants, soaps, detergents, biocides and water treatments

2.3 Programs Operated by the Private Sector

The NIST 1992 *Directory of Professional/Trade Organization Laboratory Accreditation/Designation Programs* identifies laboratory accreditation programs addressing 28 different industry and product areas. Nearly all of these programs accredit or recognize laboratories that perform specific routine tests on products. Programs in half of the industry/product areas overlap in scope with laboratory oversight programs conducted by the Federal government or state/local governments. The largest area by far is construction materials, with 19 different organizations identified that accredit laboratories performing tests on materials or products used in construction. Many of these programs duplicate each other and programs

conducted by the Federal government (e.g., the Department of Housing and Urban Development and the NIST National Voluntary Laboratory Accreditation Program). Consequently, providing a framework within which to achieve increased uniformity and reciprocal recognition within this group of programs is an important opportunity for NACLA.

Following is a listing of private sector programs that fall into the two categories identified in Exhibit 1: Programs that overlap in scope with Federal or state government programs and Programs that have a unique scope and purpose, organized by industry or product area.

Programs that overlap in scope with Federal or state government programs

Agricultural Products:

American Oil Chemists Society
National Soybean Processors Association

Blood and Human Tissue:

American Association of Blood Banks

Boating Equipment:

National Marine Manufacturers Association

Construction Materials:

American Architectural Manufacturers Association
American Association of Laboratory Accreditation
American Institute of Steel Construction, Inc.
Associated Laboratories, Inc.
Board of Accreditation of Concrete Testing Laboratories of North Carolina
Building Officials and Code Administrators, Inc.
Cellulose Industry Standards Enforcement Program
Council of American Building Officials/National Evaluation Service
ETL Testing Laboratories, Inc. Laboratory Approval Programs for Certification Program Testing
International Association of Plumbing and Mechanical Officials
International Conference of Building Officials
Kitchen Cabinet Manufacturers Association
MTL Certification Services
American Society of Mechanical Engineers/National Board of Boiler and Pressure Vessel Inspection
National Certified Testing Laboratories, Inc.
National Electrical Testing Association
NSF International
National Wood Window and Door Association
Southern Building Code Congress International, Inc.

Drinking Water, Drinking Water Additives and Water Handling Devices:

American Association of Laboratory Accreditation
NSF International

Electrical Equipment:

American Association of Laboratory Accreditation
International Electrotechnical Commission Quality Assessment System for Electronic Components
MET Electrical Testing Company, Inc./Approval of Laboratories for use in MET Certification Program
The United States National Electronic Components Quality Assessment System, Electronic Components Certification Board

Environmental Testing:

American Association of Laboratory Accreditation

Industrial Hygiene Laboratory Analysis and Product Testing:

American Industrial Hygiene Association
National Association of Independent Laboratories for Protective Equipment Testing

Laboratory Animal Care Facilities:

American Association for the Accreditation of Laboratory Animal Care

Medical Testing:

American Association of Laboratory Accreditation
College of American Pathologists Laboratory Accreditation Program

Road and Paving Materials:

American Association of State Highway Transportation Officials (Accreditation in conjunction with NIST)
American Association of State Highway Transportation Officials/Materials Reference Laboratory
American Society of Testing Materials/Cement and Concrete Reference Laboratory

Solar Collectors and Solar Domestic Water Heaters:

Solar Rating and Certification Corporation

Transportation Containers:

National Safe Transit Association, Technical Verification Program

Programs that have a unique scope and purpose

Air Movement and Control Equipment:

Air Movement and Control Association

Computers and Communications Equipment:

Corporation for Open Systems International
MET Electrical Testing Company, Inc./Approval of Laboratories for use in MET Certification Program

Dental Devices:

National Association of Dental Laboratories National Board for the Certification of Dental Laboratories

Glass and Glass Products:

Insulating Glass Certification Council
Safety Glazing Certification Council/Approved Testing Laboratories for Testing in the ANSI and Consumer Product Safety Commission

Lubricating Oil:

American Society of Testing Materials

Medical Devices:

MET Electrical Testing Company, Inc./Approval of Laboratories for use in MET Certification Program

Motor Vehicles:

American Association of Laboratory Accreditation
American Association of Motor Vehicle Administration

Offshore Oil and Gas Operations:

American Society of Mechanical Engineers Safety and Pollution Prevention Equipment Program

Railroad Equipment and Materials:

Association of American Railroads

Treated Wood:

American Wood Preservers Bureau

3.0 PHASE II: COMPARISON OF SELECTED EXISTING FEDERAL LABORATORY ACCREDITATION STANDARDS WITH ISO/IEC GUIDE 25

This phase of the study consisted of a comparison of laboratory accreditation standards used by five selected Federal government programs with the standards included in: "*General Requirements for the Competency of Calibration and Testing Laboratories (ISO/IEC Guide 25-1990)*," hereinafter referred to as ISO 25. The purpose of this comparison analysis was to provide NIST and the National Conference on Laboratory Accreditation (NACLA) with an initial assessment of the extent to which laboratory accreditation programs in the Federal government utilize standards that examine the same characteristics as do the ISO standards. NIST and NACLA can use this analysis to consider the extent to which a NACLA-recognized accreditation based on the ISO 25 standards might serve as a uniform national standard common to all U.S. laboratory accreditation programs.

The analysis compared the standards published by five Federal programs with ISO 25. The documents used for the comparison were:

1. The **National Environmental Laboratory Accreditation Conference (NELAC)** standards for accreditation of environmental testing laboratories (published by the U.S. Environmental Protection Agency as of July 24, 1996);
2. The Department of Health and Human Services, Alcohol, Drug Abuse, and Mental Health Administration's **Mandatory Guidelines for Federal Workplace Drug Testing Programs**, published in the *Federal Register* on April 11, 1988 (53 FR 11970 - 11989) and amended on June 9, 1994 ;
3. The Department of Health and Human Services, Food and Drug Administration's standards for **Good Laboratory Practice for Nonclinical Laboratory Studies (GLP)**, as published on April 1, 1996 (21 CFR Part 58);
4. The National Institute of Standards and Technology procedures and general requirements for the **National Voluntary Laboratory Accreditation Program**, published in March of 1994 (NIST Handbook 150); and
5. The U. S. Environmental Protection Agency laboratory quality systems requirements for the **National Lead Laboratory Accreditation Program**, published on April 30, 1993.

The standards included in each of these references were compared, line by line, to ISO 25, to determine the extent to which they are identical or substantially similar.

Results

Exhibit 2 summarizes the extent of overlap between the ISO 25 standards and each of the five Federal programs examined. Of those, only the NELAC and NVLAP standards include all the requirements of ISO 25. During 1996, NELAC made a deliberate effort to ensure that the quality systems requirements of the NELAC standards are as consistent with ISO 25 as possible. Consequently, the NELAC standards include all of ISO 25 requirements and, in most cases, utilize the same language as ISO 25. Similarly, the NVLAP procedures and general requirements have been specifically designed to include all aspects of ISO 25. Both the NELAC and NVLAP standards also include requirements that address laboratory performance characteristics beyond the scope of ISO 25. Consequently, a NACLA-recognized accreditation based on ISO 25 would provide both NELAC accrediting authorities (principally environmental programs at the state level) and NVLAP with an initial assessment of general laboratory characteristics. By relying on a NACLA recognition process, NELAC and NVLAP could focus the scope of their laboratory assessments on those performance characteristics unique to their programs.

Overlap between the ISO 25 standards and each of the Federal Workplace Drug Testing Program, the Good Laboratory Practices (GLP) program, and the National Lead Laboratory Accreditation program³ was less than for NELAC and NVLAP. In all three cases, most of the principal topics covered by ISO 25 were also addressed by the program standards. In many instances, however, the program standards were less specific and detailed than ISO 25. For example, while all three programs included requirements for the contents of laboratory reports, none included all the items explicitly required by ISO 25. The ISO Guide lists 16 items which must be included in all reports:

1. A title
2. Name and address of the laboratory
3. Unique identification of the report and of each page, and the total number of pages
4. Name and address of the client, where appropriate
5. Description/identification of the item tested or calibrated
6. Characterization of the item tested or calibrated
7. Condition of the item

³ To implement the National Lead Laboratory Accreditation program, EPA maintains a Memorandum of Agreement with both the American Association for Laboratory Accreditation (A2LA) and the American Industrial Hygiene Association (AIHA) to conduct laboratory assessments and recommend laboratories for accreditation. A2LA evaluates all laboratories against ISO 25 as well as the specific requirements of the National Lead Laboratory Accreditation Program.

8. Date of receipt of the item and date of testing
9. Identification of the test method used
10. Reference to sampling procedures used, if any
11. Any deviations from the published method
12. The results of testing and any supporting data
13. A statement of the estimated uncertainty
14. Signature and title of the responsible individual, and date of issue
15. A statement that the results apply only to the item tested, where appropriate
16. A statement that the report or certificate shall not be partially duplicated without the written approval of the laboratory.

The GLP standards included explicit requirements for 9 of the 16 elements; the Federal Workplace Drug Testing Program standards included explicit requirements for only 3 of the 16 elements; the National Lead Laboratory Accreditation program standards require 5 of the 16 elements. Other areas of difference in the level of detail include standards for quality systems, laboratory facility environment, maintenance of equipment and reference materials, measurement traceability and calibration, and test methods.

Exhibit 2 provides this analysis for each of the elements of ISO 25. In some cases, notes indicate differences between the program standards and the ISO 25 standards. In these cases, the ISO standards are generally more comprehensive than the program standards. Consequently, laboratories meeting the ISO 25 standard would likely be found to comply with the program standards as well. In one case, a conflict was identified between ISO 25 and the program standards. ISO 25 includes provisions for qualifying subcontractor laboratories to provide services as needed. The Federal Workplace Drug Testing Program standards strictly prohibit the use of subcontractor laboratories and this difference in policy is noted in Exhibit 2. The GLP program standards do not address the use of subcontractor laboratories, presumably because nonclinical drug testing methods generally require that all tests be performed at one site, and hence are not conducive to subcontracting. Standards for the National Lead Laboratory Accreditation Program also do not address subcontracting.

Two areas addressed by ISO 25 are not addressed by the Federal Workplace Drug Testing Program, the GLP Program, and the National Lead Laboratory Accreditation Program. These are standards for procurement of outside support and supplies and standards for addressing client complaints. The current ISO requirements in these areas do not conflict with standards in any of the three Federal programs, however.

EXHIBIT 2
SUMMARY TABLE COMPARING EXISTING STANDARDS WITH ISO 25
FOR SELECTED FEDERAL LABORATORY ACCREDITATION PROGRAMS

Key
NELAC: National Environmental Laboratory Accreditation Conference
DHHS: The Department of Health and Human Services, Alcohol, Drug Abuse, and Mental Health Administration's Federal Workplace Drug Testing Laboratory Accreditation Program
GLP: The Department of Health and Human Services, Food and Drug Administration's Good Laboratory Practices for Nonclinical Laboratories Program
NVLAP: The National Institute of Standards and Technology National Voluntary Laboratory Accreditation Program
Lead: The U. S. Environmental Protection Agency's National Lead Laboratory Accreditation Program

ISO SECTION AND REQUIREMENT		NELAC	DHHS	GLP	NVLAP	Lead	COMMENTS
4. Organization & Management							
4.1	a) managerial staff required	✓	✓	✓	✓		GLP standards specify designation of a technically qualified Study Director.
	b) personnel free from COI	✓			✓		
	c) organized for independence in judgement and integrity	✓			✓		
	d) document responsibilities of managers and all personnel affecting quality	✓			✓		
	e) supervision by persons familiar with methods and procedures	✓	✓	✓	✓		
	f) technical manager responsible for technical operations	✓		✓	✓	✓	

ISO SECTION AND REQUIREMENT					NELAC	DHHS	GLP	NVLAP	Lead	COMMENTS
g) quality manager (QM) responsible for the quality system with direct access to the highest level of management					✓	✓	✓	✓		DHHS standards specify that the Quality Manager may be the Laboratory Director. GLP standards do not explicitly require direct access to the highest level of management. Standards applicable to Internal audits and audit reports. Includes requirements that the QA staff report directly to management.
h) nominate deputies for the QM					✓			✓		
i) document policies and procedures to protect clients' CBI and proprietary rights					✓			✓		
j) participate in interlaboratory comparisons or proficiency testing					✓			✓		
5. Quality System, Audit and Review										
5.1 Establish and maintain a quality system. Document the elements of the system. Make documentation available to staff. Ensure implementation.					✓	✓	✓	✓	✓	
5.2 Quality manual shall state policies and procedures established to meet these standards. It shall contain:					✓			✓	✓	
a) a quality policy statement					✓			✓	✓	
b) laboratory organization & management					✓			✓	✓	
c) relations between management, technical operations, support services and the quality system					✓			✓		
d) procedures for control and maintenance of documentation					✓			✓		

ISO SECTION AND REQUIREMENT	NELAC	DHHS	GLP	NVLAP	Lead	COMMENTS
e) job descriptions for key staff and references to the job descriptions of other staff	✓			✓	✓	
f) identification of laboratory signatories	✓			✓		
g) procedures for achieving, traceability of measurements	✓			✓		
h) scope of calibration or testing services	✓			✓		
i) arrangements for reviewing all work to ensure laboratory has required facilities and resources before commencing	✓			✓		
j) reference to calibration, verification and/or test procedures used	✓	✓	✓	✓	✓	
k) procedures for handling calibrations a/o test items	✓			✓	✓	
l) reference to major equipment and reference measurement standards used	✓			✓		
m) reference to procedures for calibration, verification and maintenance of equipment	✓			✓	✓	
n) reference to verification practices including interlaboratory comparisons, proficiency testing, use of reference materials, and internal QC schemes	✓	✓		✓		

ISO SECTION AND REQUIREMENT		NELAC	DHHS	GLP	NVLAP	Lead	COMMENTS
	o) procedures to be followed for feedback and corrective action when discrepancies are detected	✓		✓	✓		
	p) arrangements for exceptionally permitting departures from policies	✓			✓		
	q) procedures for dealing with complaints	✓			✓		
	r) procedures for protecting confidentiality and proprietary rights	✓			✓		
	s) procedures for audit and review	✓		✓	✓	✓	
5.3	arrange for audits at appropriate intervals; audits to be carried out by trained and qualified staff who are independent of the activity; take immediate action where audits indicate a problem, notify clients where audits indicate a problem.	✓		✓	✓		
5.4	review the quality system at least once each year and introduce any necessary changes or improvements	✓		✓	✓		GLP standards require periodic review consistent with the study schedule. Some studies are designed to be completed in less than one year.
5.5	document all audits, reviews and corrective actions	✓		✓	✓		
5.6	Implement checks to ensure quality, including:	✓			✓		
	a) internal QC schemes	✓	✓		✓		
	b) participation in proficiency testing or interlaboratory comparisons	✓	✓		✓		
	c) use of certified reference materials or secondary reference materials	✓			✓		

ISO SECTION AND REQUIREMENT		NELAC	DHHS	GLP	NVLAP	Lead	COMMENTS
d)	replicate testing using different methods	✓	✓		✓		
e)	retesting of retained items	✓	✓		✓		
f)	correlation of results for different characteristics	✓			✓		
6. Personnel							
6.1	sufficient personnel with necessary education, training, technical knowledge and experience	✓		✓	✓	✓	
6.2	ensure that personnel training is kept up-to-date.	✓	✓		✓		
6.3	maintain records on staff qualifications, training, skills and experience.	✓	✓	✓	✓	✓	
7. Accommodation and Environment							
7.1	proper areas, energy sources, lighting, heating, and ventilation	✓			✓	✓	
7.2	environment does not invalidate results	✓		✓	✓		
7.3	facilities for effective monitoring, control and recording of environmental conditions	✓			✓		
7.4	effective separation between areas	✓		✓	✓		
7.5	access to and use of all areas affecting quality shall be defined and controlled	✓			✓		

ISO SECTION AND REQUIREMENT		NELAC	DHHS	GLP	NVLAP	Lead	COMMENTS
7.6	adequate measures to ensure good housekeeping	✓		✓	✓		
8. Equipment and Reference Materials							
8.1	furnished with all required equipment	✓		✓	✓	✓	Lead program guidance states that all requirements of ISO Guide 25 related to equipment maintenance and calibration apply.
8.2	all equipment properly maintained	✓		✓	✓	✓	
8.3	all equipment and standards marked or labeled to indicate calibration status	✓	✓		✓	✓	Lead program guidance states that all requirements of ISO Guide 25 related to equipment maintenance and calibration apply.
8.4	maintain records for all equipment and reference materials significant to all calibrations or tests performed; records shall include:	✓		✓	✓	✓	
	a) name of the equipment item	✓			✓	✓	
	b) manufacturer's name, type identification, and serial number or other unique identifier	✓			✓	✓	
	c) date received and date placed in service	✓	✓		✓	✓	NVLAP standards state that this requirement is not mandatory for initial accreditation.
	d) current location	✓			✓	✓	
	e) condition when received (new, used, reconditioned)	✓			✓	✓	
	f) copy of manufacturer's instructions	✓			✓	✓	
	g) dates and results of calibrations a/o verifications and date of the next calibration a/o verification	✓	✓	✓	✓	✓	DHHS standards include this technical requirement but do not include a specific requirement for maintaining these records.

ISO SECTION AND REQUIREMENT		NELAC	DHHS	GLP	NVLAP	Lead	COMMENTS
h) details of maintenance carried out and planned		✓	✓	✓	✓	✓	DHHS standards include this technical requirement but do not include a specific requirement for maintaining these records.
i) history of any damage, malfunction, modification or repair		✓		✓	✓	✓	
9. Measurement Traceability and Calibration							
9.1	all equipment must be calibrated or verified prior to placement in service; laboratory must have a program for calibration/verification of equipment	✓		✓	✓	✓	
9.2	program must ensure that all measurements are traceable to national standards where available	✓			✓	✓	NVLAP standards require application of specific procedures included in program guidance.
9.3	where national standards are not available, laboratory must provide evidence of correlation of results (e.g., by participation in an interlaboratory comparison program)	✓			✓	✓	
9.4	reference standards shall be used for calibration only	✓			✓	✓	
9.5	reference standards must be calibrated by a body that can provide traceability to a national standard	✓			✓	✓	
9.6	reference standards and equipment shall be subjected to in-service checks between calibrations/verifications	✓			✓	✓	
9.7	reference materials shall be traceable to national or international standards	✓			✓	✓	

ISO SECTION AND REQUIREMENT		NELAC	DHHS	GLP	NVLAP	Lead	COMMENTS
10. Calibration and Test Methods							
10.1	laboratory must have documented instructions on operation of equipment, handling and preparation of items for testing; all instructions/manuals must be maintained up-to-date	✓		✓	✓	✓	
10.2	must use proper methods for all calibrations, tests and related activities	✓	✓	✓	✓	✓	
10.3	where no methods are specified, must select methods that have been published in international or national standards published by reputable technical organizations or in relevant scientific periodicals	✓		✓	✓		Lead standards state that all methods are specified at 40 CFR 1910.
10.4	where nonstandard methods are used, they must be approved by the client, documented, validated, and available	✓		✓	✓	✓	Lead standards state that all methods are specified at 40 CFR 1910. Alternative methods must be documented and validated.
10.5	Documented procedures for sampling and appropriate statistical methods must be used	✓		✓	✓		
10.6	Calculations and data transfers subject to appropriate checks	✓		✓	✓	✓	
10.7	where computers are used to handle data, the laboratory must ensure that: a) all ISO 25 requirements are complied with	✓		✓	✓		NELAC standards require compliance with EPA's "Good Automated Laboratory Practices" guidelines. GLP standards require a Standard Operating Procedure for data handling. There are no explicit specifications similar to ISO 25.
	b) computer software is documented and appropriate	✓			✓	✓	

ISO SECTION AND REQUIREMENT		NELAC	DHHS	GLP	NVLAP	Lead	COMMENTS
c)	procedures for protecting data integrity are used	✓			✓		
d)	hardware is maintained properly	✓			✓		
e)	data security procedures are established and implemented	✓			✓		
10.8	Laboratory must have documented procedures for purchase, reception and storage of consumables	✓			✓		
11. Handling of Calibration and Test Items							
11.1	must have documented system for uniquely identifying items to be tested	✓	✓	✓	✓	✓	
11.2	condition of all items must be documented upon receipt	✓	✓	✓	✓	✓	
11.3	must have documented procedures and facilities to prevent deterioration or damage to test items; environmental conditions must be monitored and documented where appropriate; security must be maintained where necessary	✓	✓	✓	✓		GLP standards require a separate storage facility and controlled access.
11.4	must have documented procedures for receipt, retention and safe disposal of test items	✓	✓	✓	✓		
12. Records							
12.1	must maintain an appropriate record system; retain and record all original observations, calculations, etc.	✓	✓	✓	✓		GLP standards are more specific than ISO 25. NVLAP standards recommend maintenance of original observations, calculations, and derived data but do not require that they be maintained by calibration laboratories.

ISO SECTION AND REQUIREMENT		NELAC	DHHS	GLP	NVLAP	Lead	COMMENTS
12.2	all records, certificates and reports must be safely stored	✓	✓	✓	✓		GLP standards are more specific than ISO 25.
13. Certificates and Reports							
13.1	all results must be reported accurately, clearly, unambiguously, and objectively	✓			✓		
13.2	each report or certificate shall include:	✓			✓	✓	
	a) a title	✓			✓		
	b) name and address of laboratory	✓		✓			
	c) unique identification of the report, and each page and the total number of pages	✓			✓		
	d) name and address of client, where appropriate	✓			✓		
	e) description/identification of the item tested	✓	✓	✓	✓		GLP standards are more specific than ISO 25.
	f) characterization and condition of the item	✓		✓	✓		GLP standards are more specific than ISO 25.
	g) date of receipt of the item and date of test	✓		✓	✓	✓	NVLAP standards recommend but do not require calibration laboratories to include date of receipt and test.
	h) identification of method used	✓	✓	✓	✓	✓	
	i) reference to sampling procedure, where used	✓		✓	✓		
	j) any deviations from the method	✓		✓	✓		
	k) results and any supporting data	✓	✓	✓	✓	✓	

ISO SECTION AND REQUIREMENT		NELAC	DHHS	GLP	NVLAP	Lead	COMMENTS
	l) a statement of estimated uncertainty	✓			✓		
	m) signature and title of responsible individual	✓		✓	✓	✓	
	n) a statement that the results apply only to the item tested, where appropriate	✓			✓		
	o) a statement that the report or certificate shall not be duplicated except in full without written consent of the laboratory	✓			✓		
13.3	any results generated by subcontractors must be identified	✓			✓		DHHS standards strictly prohibit the use of subcontractors.
13.4	reports should be designed to be easily read and understood	✓			✓		
13.5	any amendments to reports or certificates must be made in writing and must identify the original report by its unique identifier	✓		✓	✓	✓	
13.6	clients must be notified promptly and in writing of any defects identified	✓			✓		
13.7	electronic transmission of data or reports must be done in accordance with procedures that ensure confidentiality and that ISO 25 is met	✓			✓		
14. Subcontracting of Calibration or Testing							

ISO SECTION AND REQUIREMENT		NELAC	DHHS	GEP	NVLAP	Lead	COMMENTS
14.1	any subcontract laboratories used must comply with ISO 25; laboratories are responsible for determining that their subcontract laboratories meet ISO 25	✓			✓		NELAC standards require that all subcontractors be determined to meet NELAC standards. DHHS standards strictly prohibit the use of subcontractors.
14.2	laboratories must maintain records of its determinations of the competency of subcontract laboratories and must maintain a register of qualified subcontract laboratories	✓			✓		DHHS standards strictly prohibit the use of subcontractors.
15. Outside Support Services and Supplies							
15.1	laboratories must use outside supplies and services that are adequate to sustain confidence in the laboratory's work	✓			✓		
15.2	laboratory must have procedures for ensuring that purchased equipment, materials or services meet requirements and are inspected prior to use	✓			✓		
15.3	laboratory must maintain records of all suppliers and service providers	✓			✓		
16. Complaints							
16.1	laboratory must have documented policies and procedures for resolution of complaints; records of complaints shall be maintained	✓			✓		
16.2	where a complaint raises doubts about the quality of the laboratory's work, an audit must be conducted promptly	✓			✓		

4.0 CONCLUSIONS

This study supports some preliminary conclusions that may guide the deliberations of the NACLA Interim Board of Directors. They are as follows:

Some significant areas of overlapping scope, inconsistent program components, and application of highly variable accreditation terminology exist in laboratory accreditation programs. NACLA should include a process for addressing these aspects of the current system in a way that will strengthen and improve the overall U.S. laboratory accreditation system. Areas of overlap and inconsistency to be addressed should include:

- Federal programs supporting government oversight of product testing or certification differ considerably in the terminology used and the status granted to laboratories. Documentation of laboratory review procedures and criteria varies from program to program and program-qualifying procedures vary from simple review of written applications to comprehensive programs requiring written applications, on-site assessments, and routine laboratory proficiency testing.
- State and local programs supporting oversight of product testing/certification, preliminary information shows considerable overlap among state/local programs and Federal programs. Provisions for reciprocal recognition between programs were found in only a limited number of settings.
- Also in the area of product testing and certification, a large number of private sector programs appear to duplicate or overlap programs conducted at the Federal and state/local levels. Indications of cooperative or reciprocal relationships were identified in only a very few areas.
- In the area of state/local government programs supporting regulatory compliance, considerable overlap may exist between Federal and state programs and among state programs. Little evidence was found of reciprocal arrangements between state programs that accredit or certify for the same purpose. In the area of environmental testing, the NELAC has begun to address issues of overlap and to promote reciprocity among state programs. Similar problems in the area of occupational safety and health remain unaddressed, however.

Existing Federal government laboratory accreditation programs differ considerably in the extent to which they address the general aspects of laboratory performance common to all testing and calibration laboratories. These general areas include: laboratory organization and management, laboratory quality systems and audits, laboratory personnel, laboratory facility considerations, equipment and reference materials, measurement traceability and calibration, testing and calibration methods, handling of test items and specimens, laboratory record keeping, laboratory reports, subcontracting practices, and laboratory practices for addressing client complaints. NACLA should include a process designed to gain consensus among Federal

government agencies concerning the value of ensuring that, at a minimum, all laboratory accreditation programs address these basic elements. NACLA should further set a goal of implementing such a minimum standard governmentwide reasonably soon. Ensuring that U.S. programs at a minimum address the components of ISO/IEC Guide 25 or its equivalent will improve the overall U.S. system and have both domestic and international benefits.

The NACLA Interim Board of Directors should consider NACLA to be an important leadership resource for the U.S. laboratory accreditation community in the future. For example, NACLA should develop and promote the application of the model used by the National Environmental Laboratory Accreditation Conference (NELAC) and the National Conference on Weights and Measures (NCWM) to achieve consensus among existing, overlapping programs in other areas, particularly where state and Federal government programs overlap. There are many other examples of areas where NACLA leadership can be applied to improve laboratory accreditation in the United States. For example, NACLA should serve as a forum for addressing issues common to numerous Federal government laboratory accreditation programs, such as:

- Proper procedures for ensuring due process in the suspension or revocation of an accreditation;
- Issues related to liquidated damages resulting from a loss of accreditation status for laboratories or loss of recognition status for accrediting bodies;
- Uniform standards for professional ethics in the accreditation process and in the laboratory industry;
- Appropriate roles for private accrediting bodies in areas typically addressed by government organizations;
- Appropriate relationships between private and public sector programs where they overlap; and
- Uniform standards for maintaining confidentiality in the accreditation process and for identifying and addressing confidentiality violations.

Leadership within the Federal government would also provide a forum for identifying areas where cooperation among government programs or the establishment of public-private partnerships might be used to make existing laboratory accreditation programs more efficient and effective. Example areas include:

- Laboratory proficiency testing and related information management and dissemination needs;
- Development and distribution of reference materials for use by laboratories;
- Application of automated information management systems; and
- Development and use of training programs.

The NACLA operating plan should therefore include provisions for bringing together representatives from all stakeholder groups to address these and other issues and develop consensus approaches to their resolution.

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